

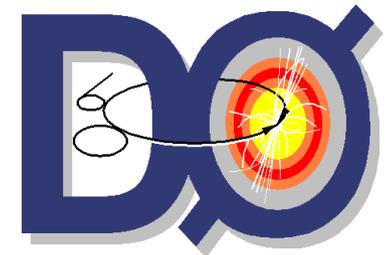
Looking for the Hidden and the Quirky at DØ

Andy Haas

*SLAC National Accelerator Laboratory /
Columbia University*

for the DØ Collaboration

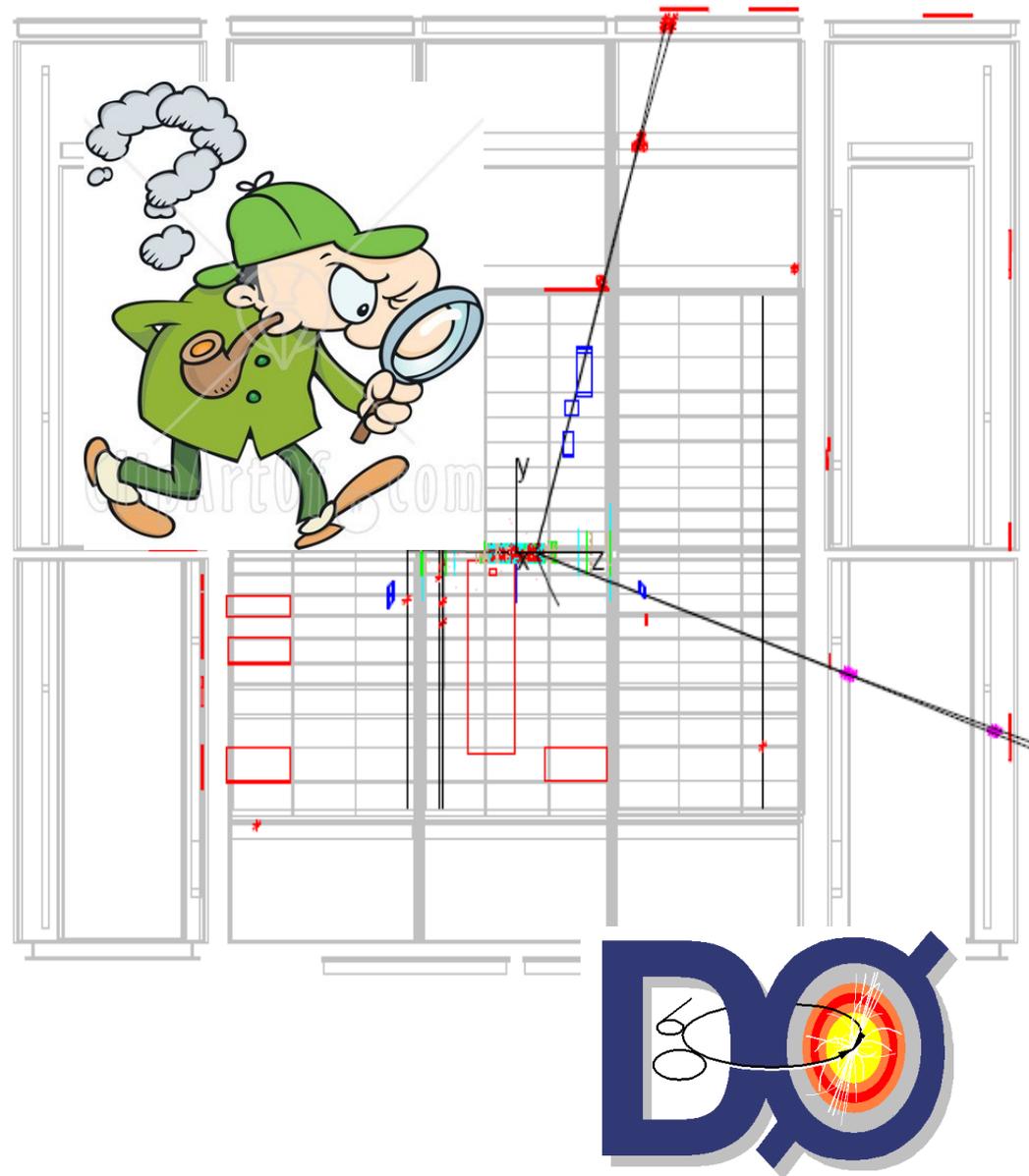
**Fermilab Wine&Cheese Seminar
September 17, 2010**



Where's the New Physics ?!

~100 D0/CDF Run II searches for new physics

- SUSY SUSY SUSY
- Lepto-quarks
- Large Extra Dimensions
- W' , Z'
- Excited quarks
- Excited leptons
- RS Gravitons
- Long-lived particles
- Fourth generation quarks
- "Model independent"
- (+ many BSM Higgs searches) ...



Where's the New Physics ?!

Is there any chance of still finding something new?

Where's the New Physics ?!

Is there any chance of still finding something new?

YES!

*Look in new places : new final states
New experimental methods – More data*

The ideal search for new physics in 2010 at the Tevatron:

- Final state or signature never studied before
or far more sensitive techniques than used before
- Experimentally practical / stands out above backgrounds
- *Bonus: well-motivated theoretically – not essential!*

$\gamma\gamma + MET$

6x more data / new methods.

Clean!

Well-motivated!

"Lepton-jets"

New signature!

Clean!

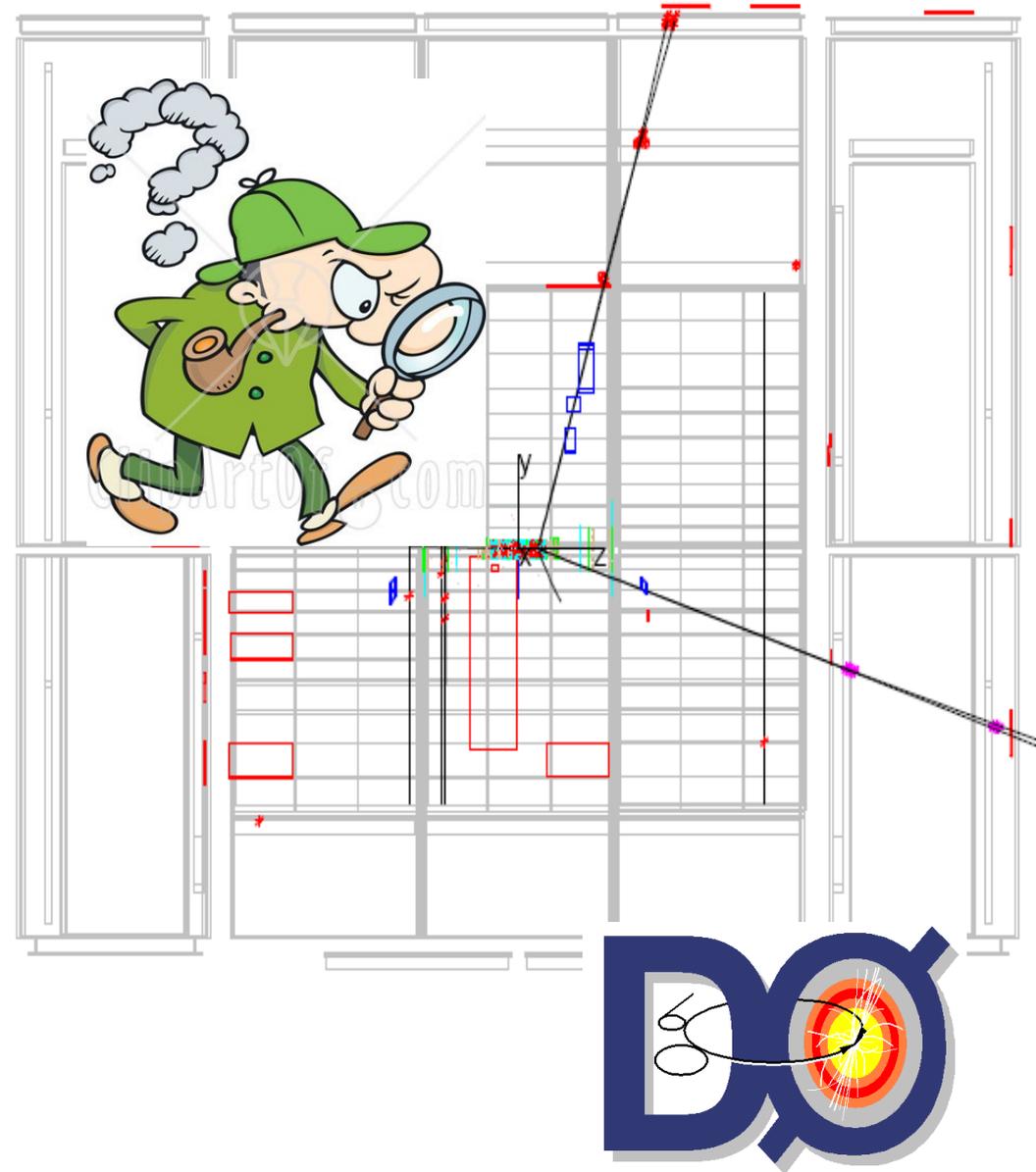
Well-motivated!

"Quirks"

New signature!

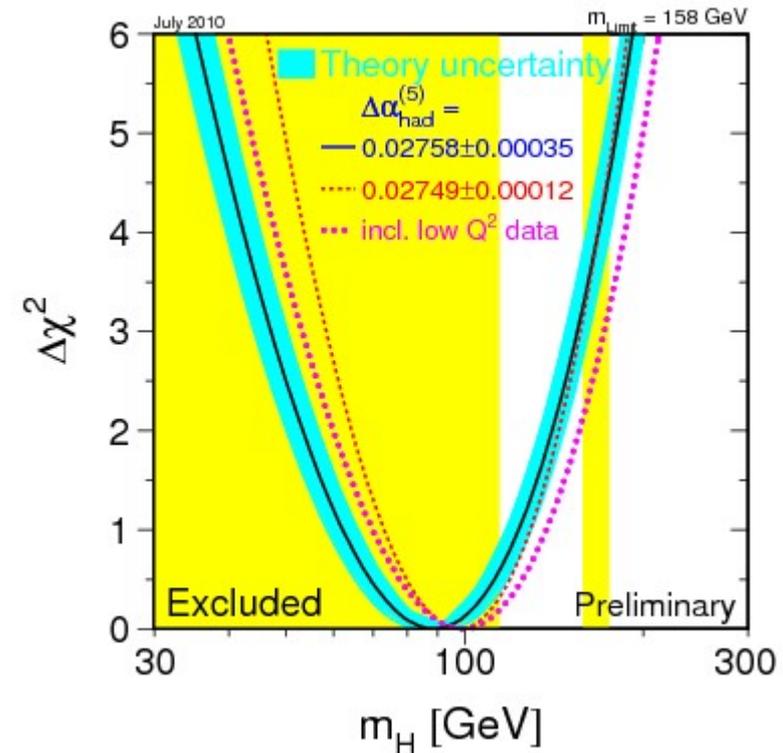
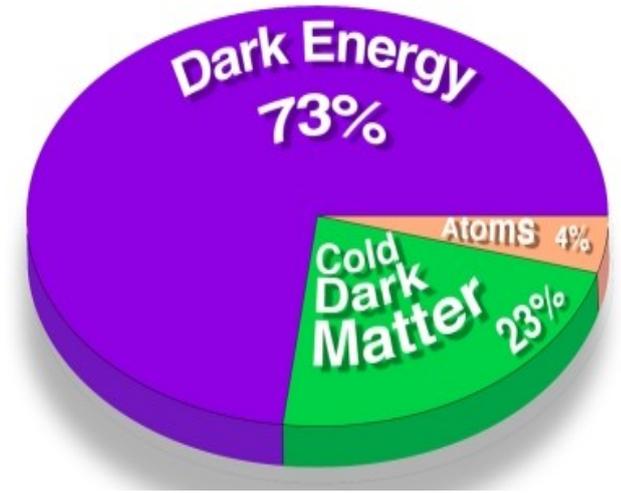
Clean!

Why not?!



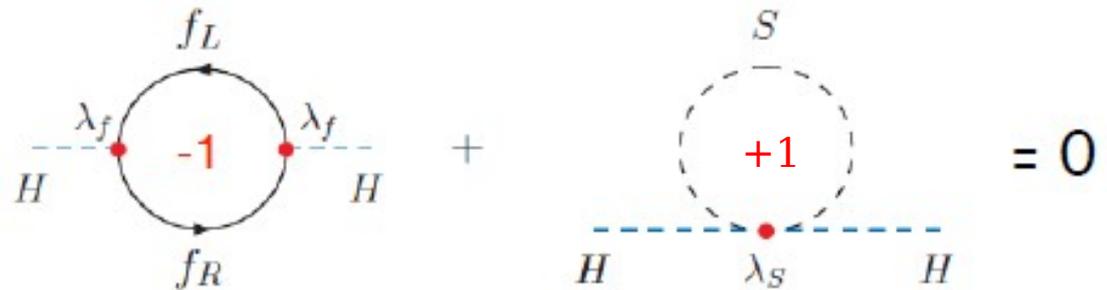
Motivation

- What is Dark Matter?
- Why is the Higgs so light (if it exists)?
The hierarchy problem...
- (*Dark energy? Gravity?*)



Motivation

Super-symmetry!



- What is Dark Matter?

Lightest SUSY particle (R-parity)

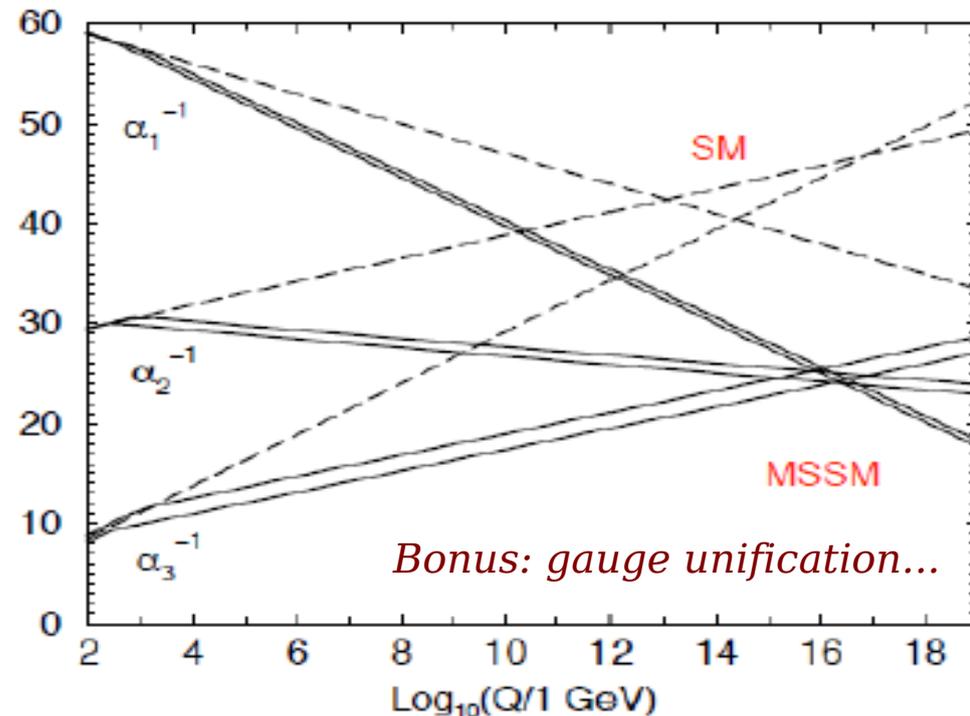
- Why is the Higgs so light (if it exists)?
The hierarchy problem...

Higgs is there
(and other Higgses too!)

It's light because SUSY
cancels quadratic divergences

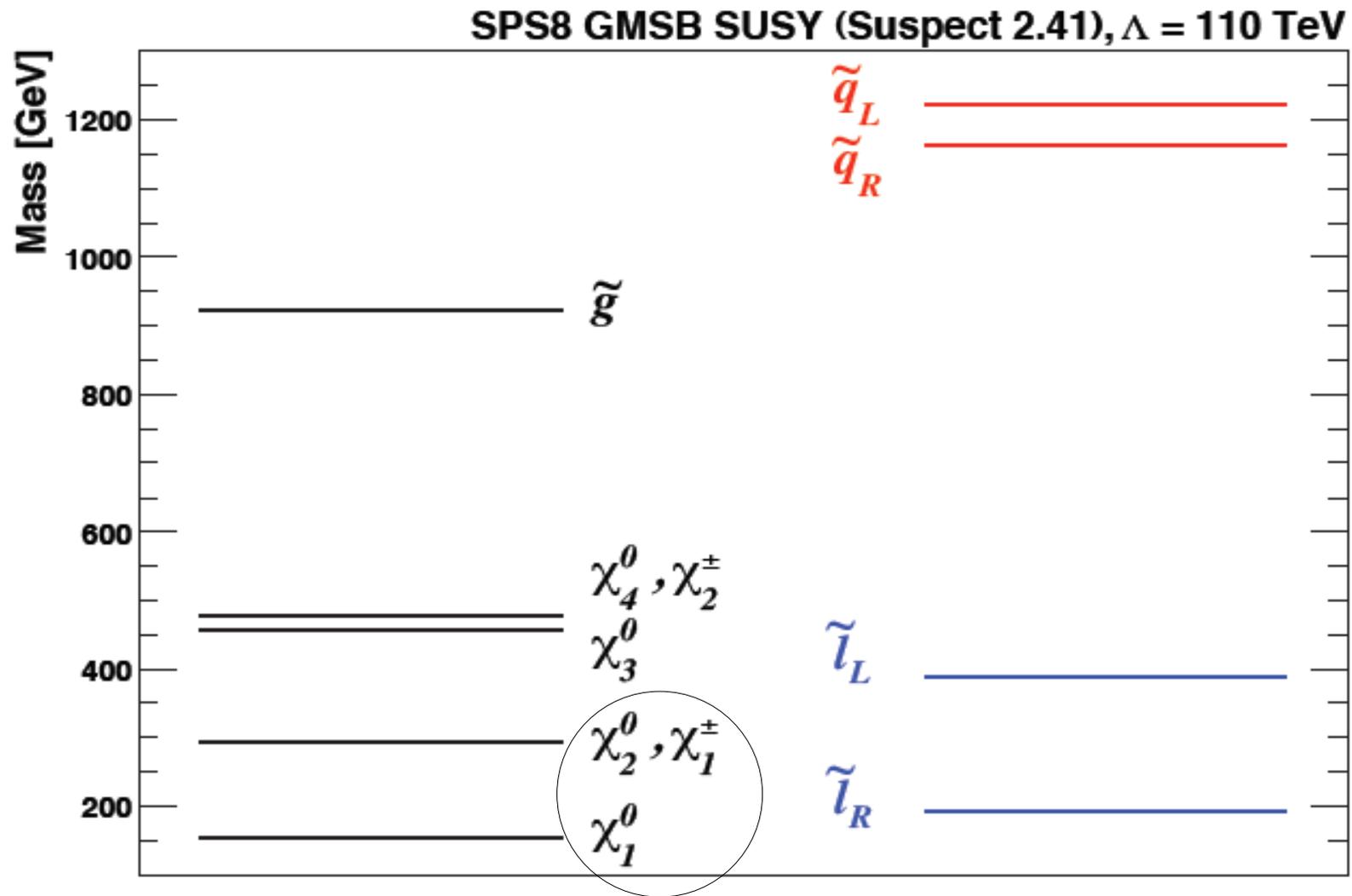
- (*Dark energy? Gravity?*)

Super-strings. Who knows.



SUSY Signatures

An example SUSY particle spectrum...



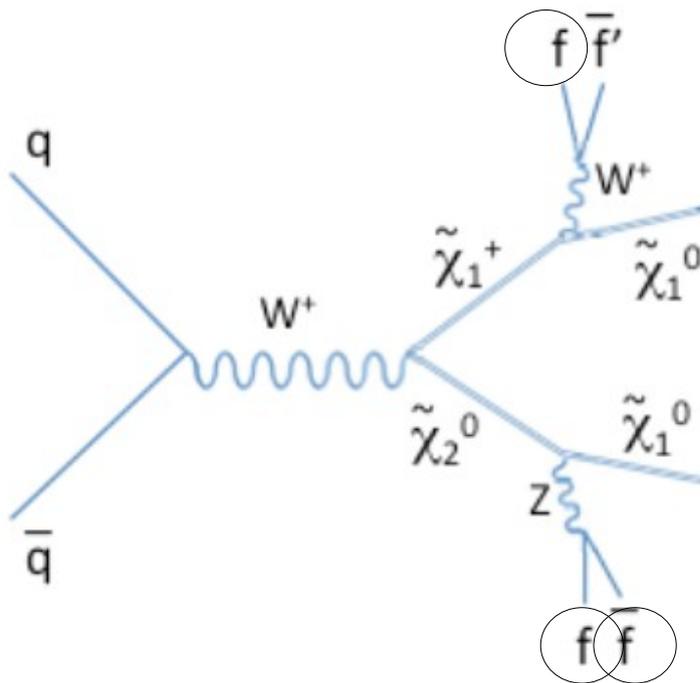
SUSY Signatures

Continuing to look for SUSY...

Example: Chargino / Neutralino production

Gravity-mediated breaking:

Neutralino is lightest SUSY particle and stable (dark matter)
- assuming R-parity



Classic
3-lepton + MET
signature

SUSY Signatures

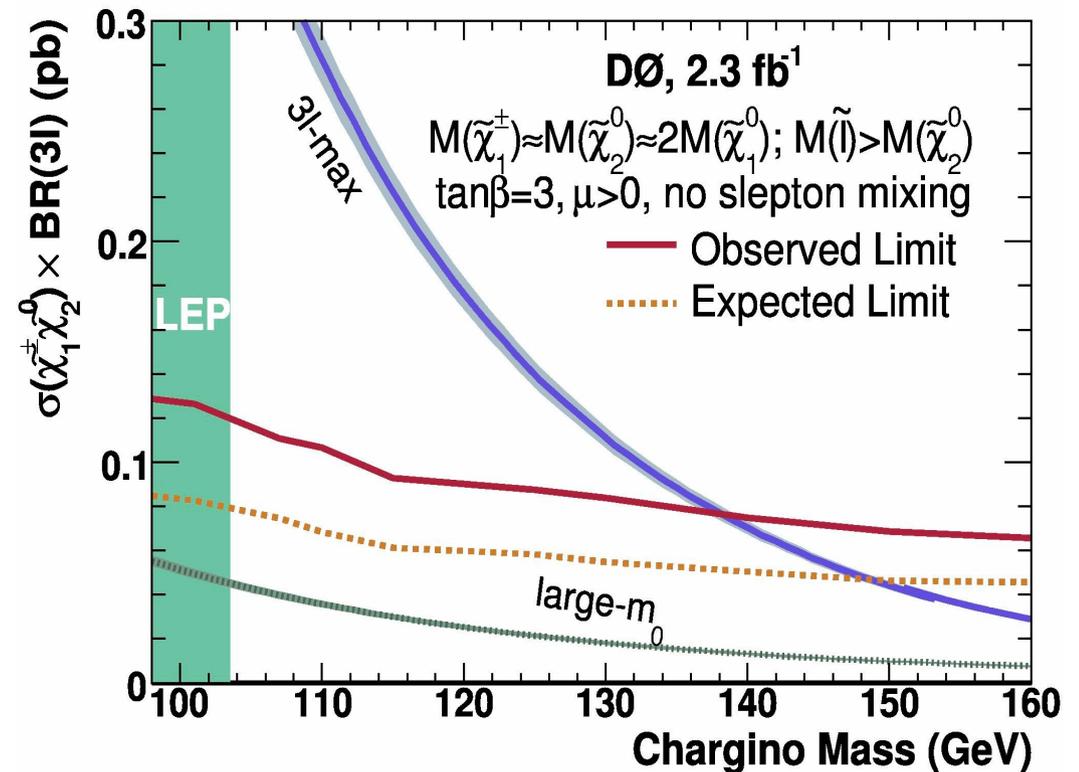
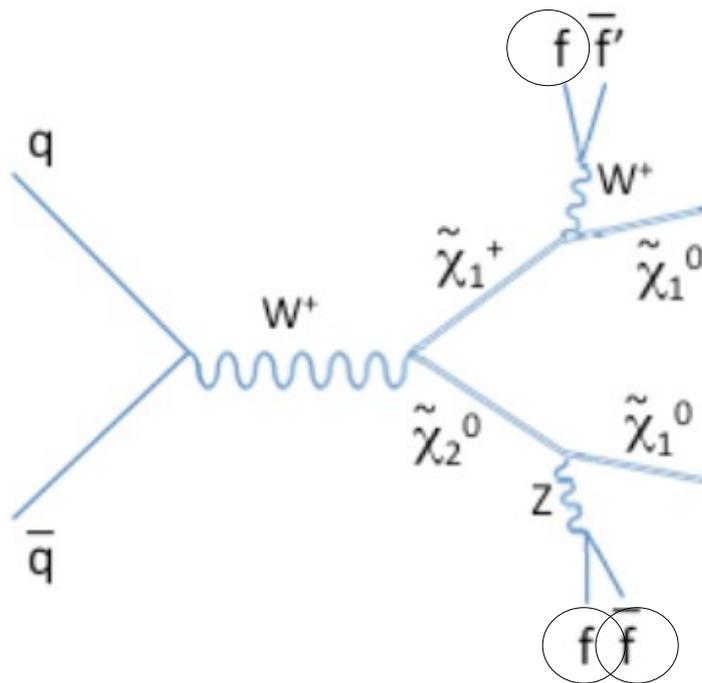
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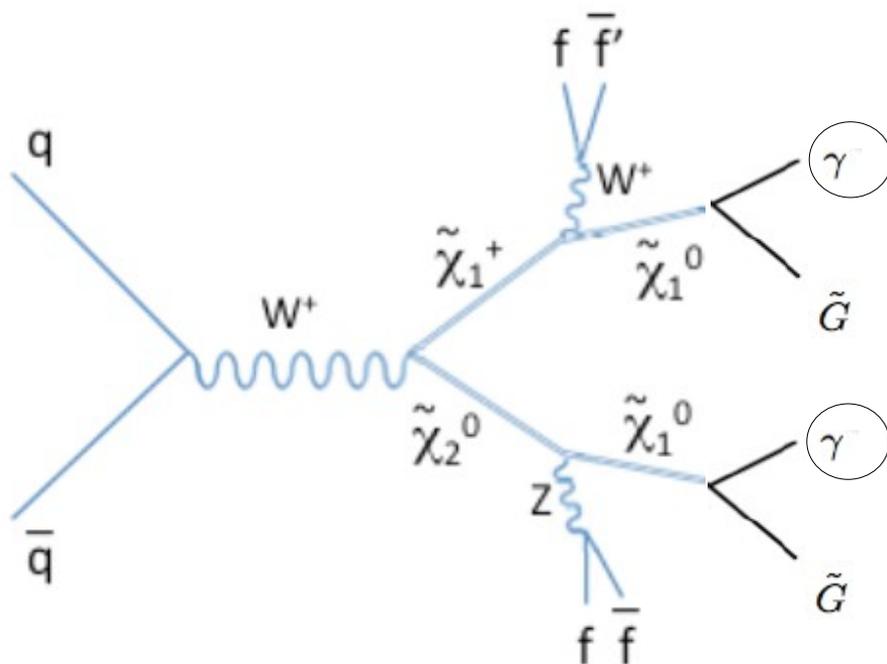
SUSY Signatures

Continuing to look for SUSY...

Example: Chargino / Neutralino production

Gauge-mediated breaking:

Neutralino decays to a photon + gravitino (really dark matter)



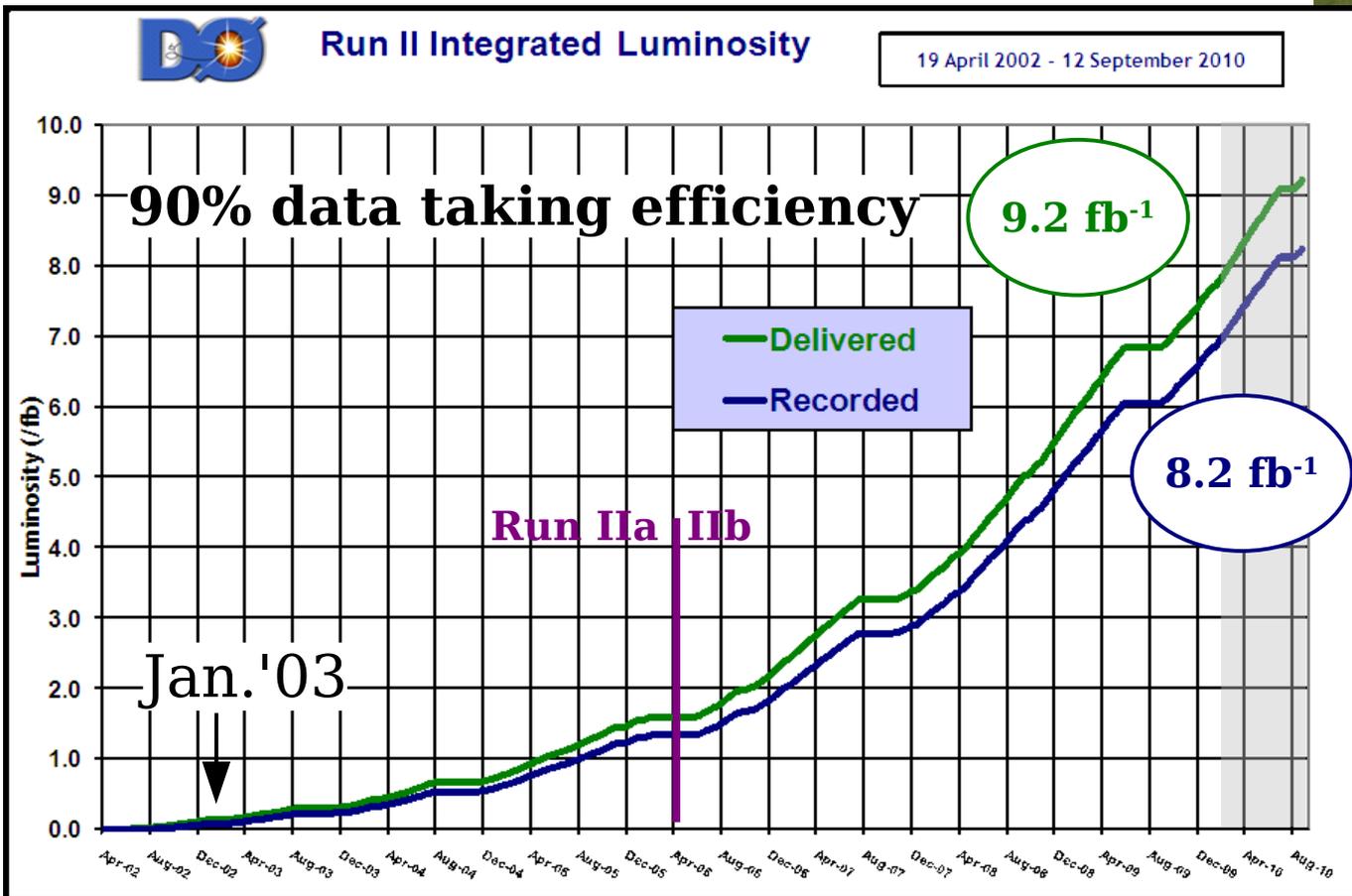
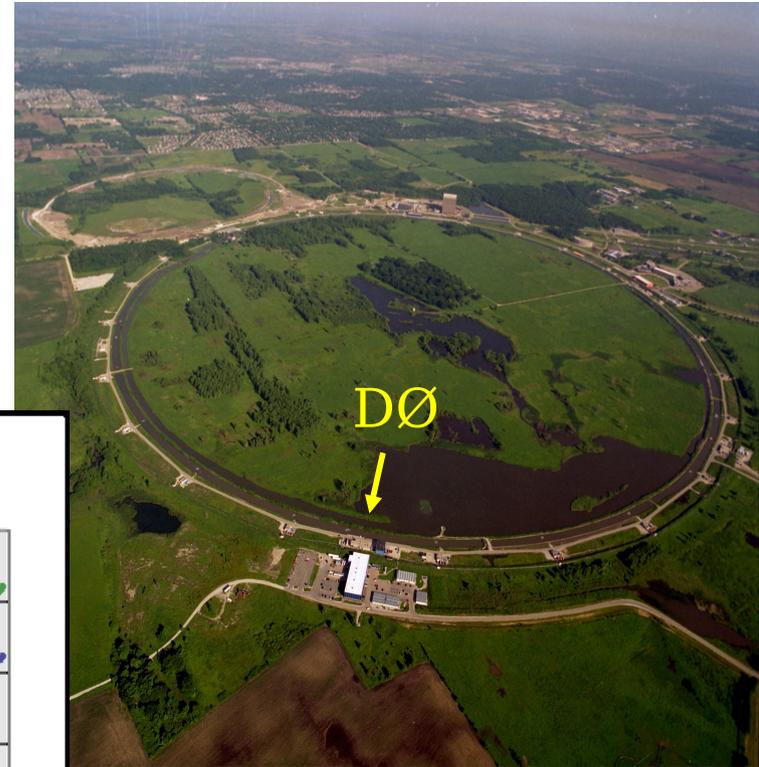
Classic
2-photon + MET
signature

***Just done with improved methods
and much more data at D0...***

Data at DØ

$p\bar{p}$ collider at 1.96 TeV

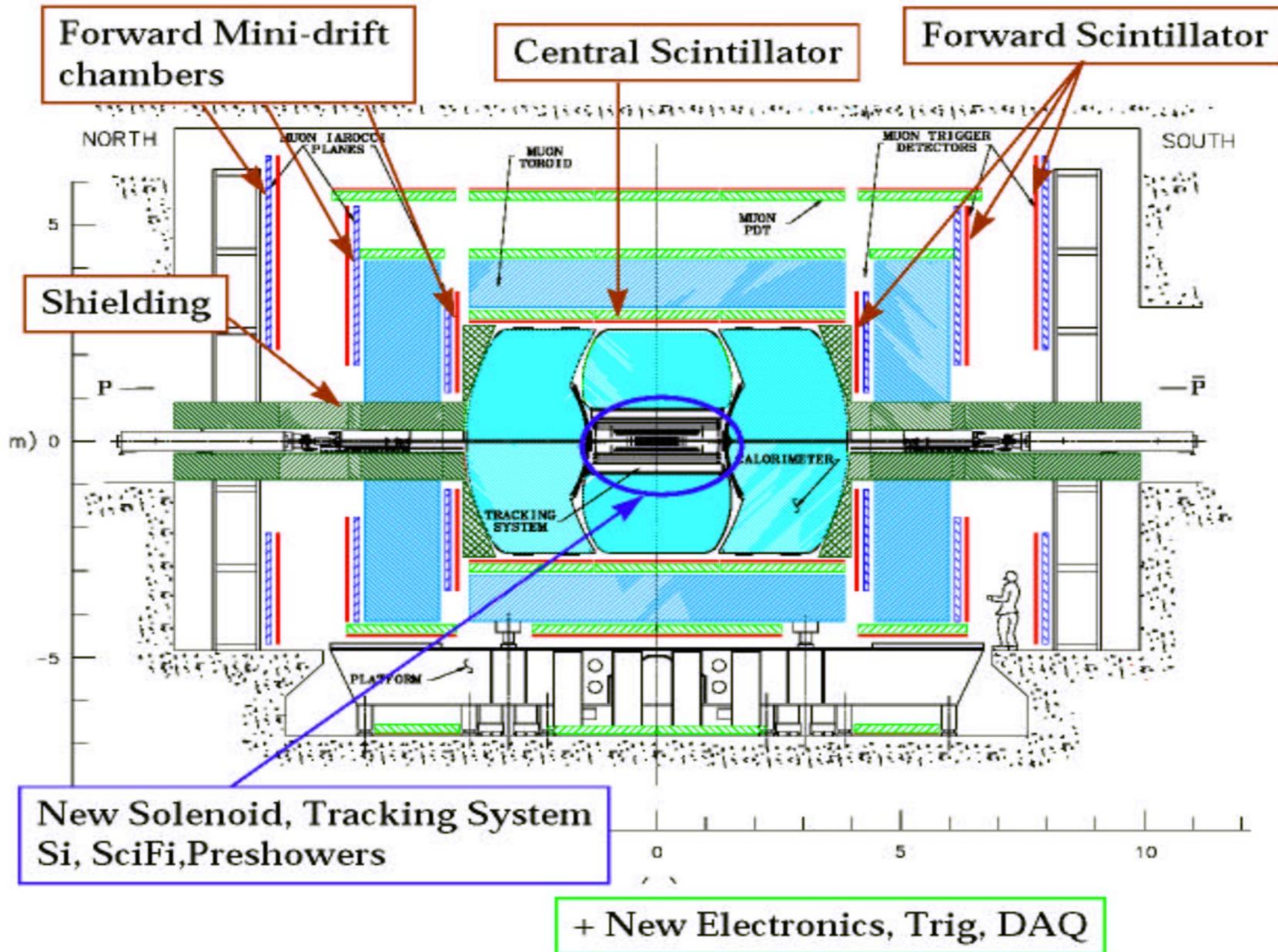
Up to 6.3 fb^{-1} analyzed in this talk



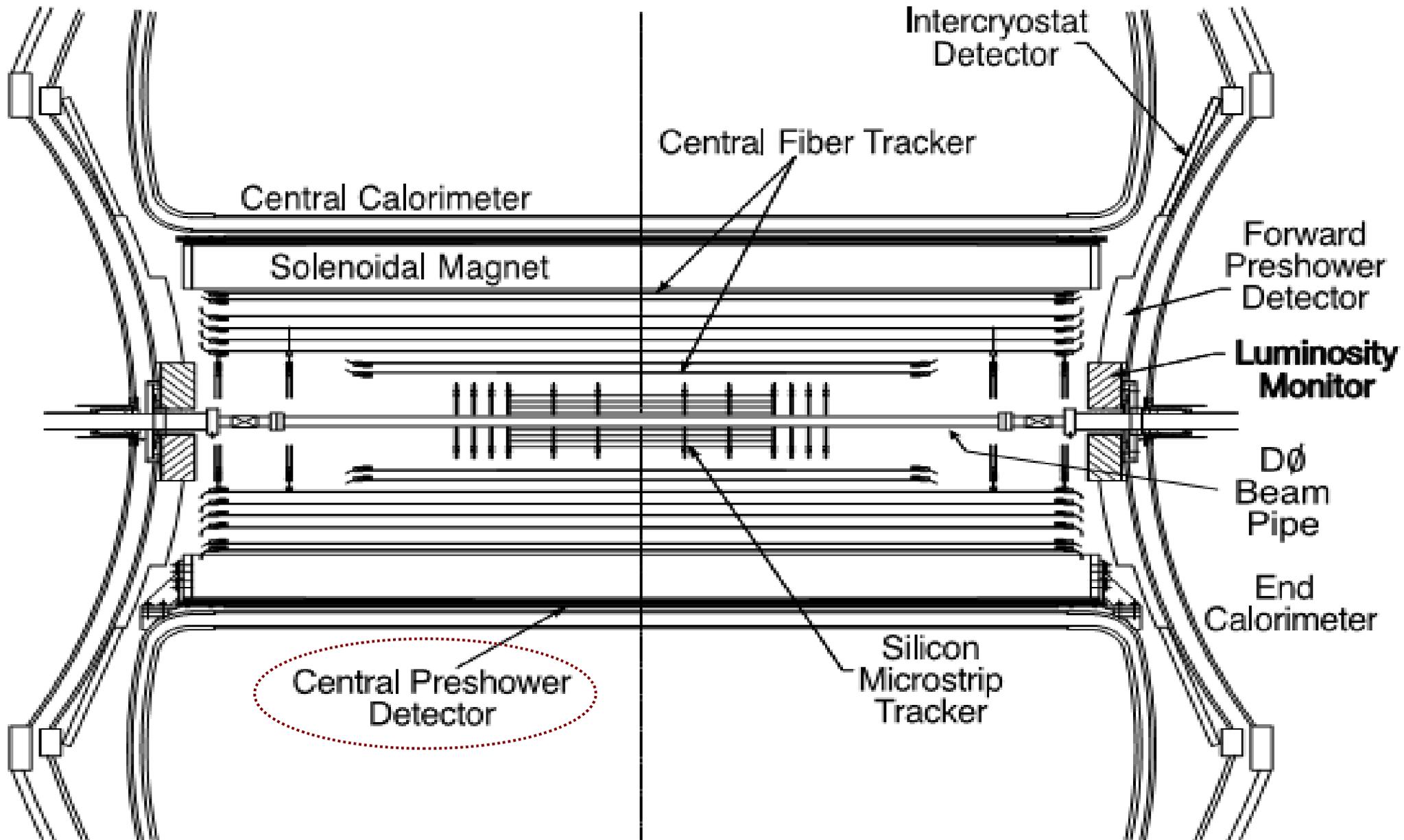
Tevatron and DØ
both performing
very well

Thanks AD!

DØ



DØ



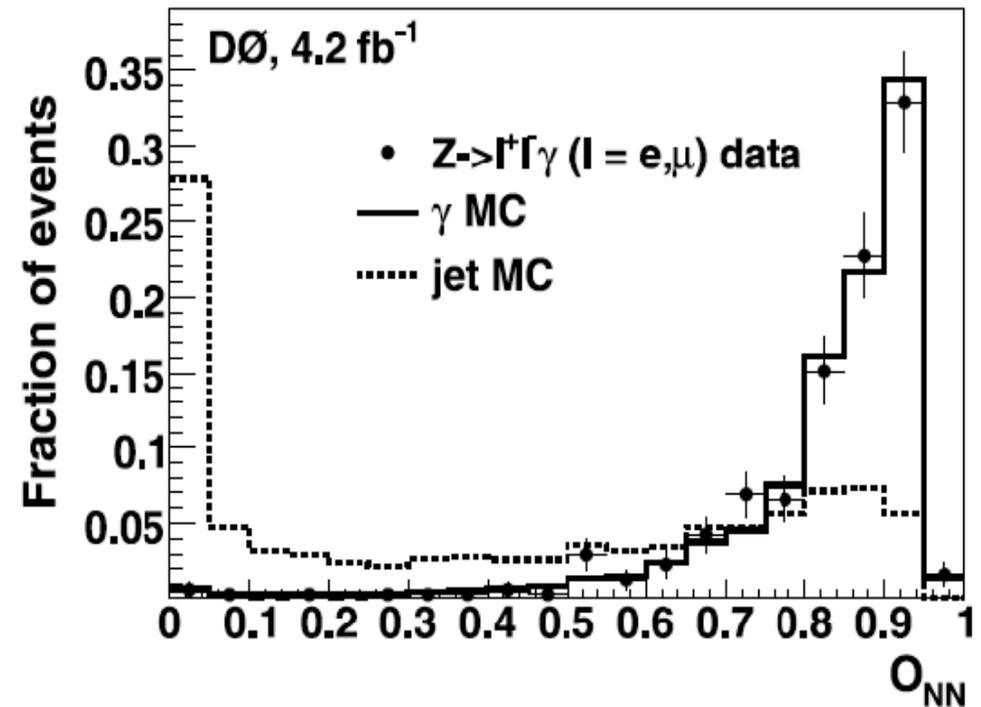
New Photon Identification

Artificial NN trained with MC to separate photons from jets

Input Variables:

- N 1st EM layer clusters ($E > 450$ MeV) w/ $\Delta R < 0.2$ w.r.t. cluster centroid.
- N 1st EM layer clusters ($E > 450$ MeV) w/ $0.2 < \Delta R < 0.4$ w.r.t. cluster centroid.
- Track isolation
- N CPS cluster w/ $\Delta R < 0.1$ w.r.t. cluster centroid.
- Energy weighted CPS RMS in ϕ

Diphoton xsec (Note 5959), PLB 690, 108 (2010)

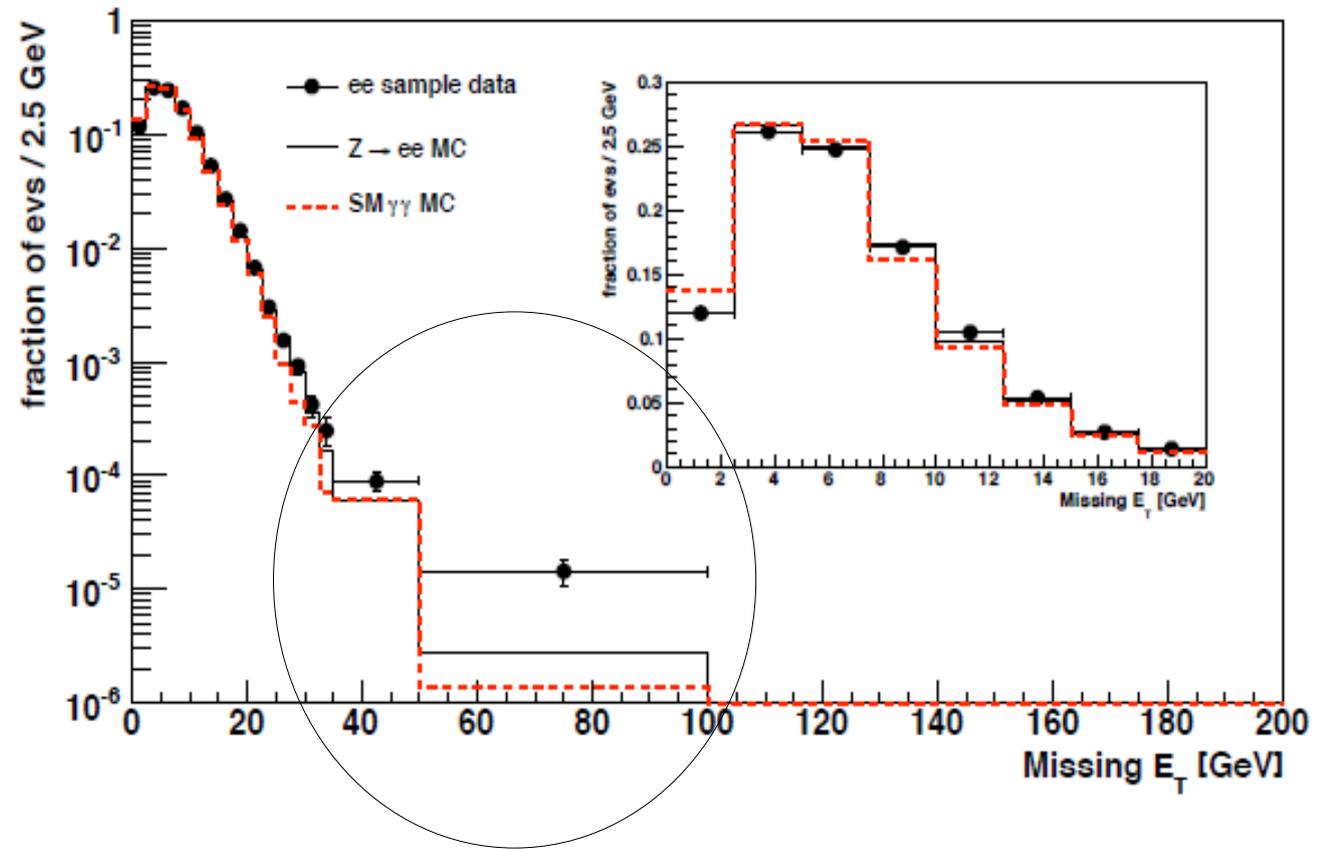


Good understanding and simulation of EM showers and jets faking photons

Tested using Z+γ and di-jet data events

Understanding the $\gamma\gamma$ +MET Background

Main background is SM $\gamma\gamma$ events with mis-measured MET



Verify modeling using Z \rightarrow ee data events

Difference between data/MC at high MET is systematic uncertainty

$\gamma\gamma + \text{MET}$

Much larger dataset

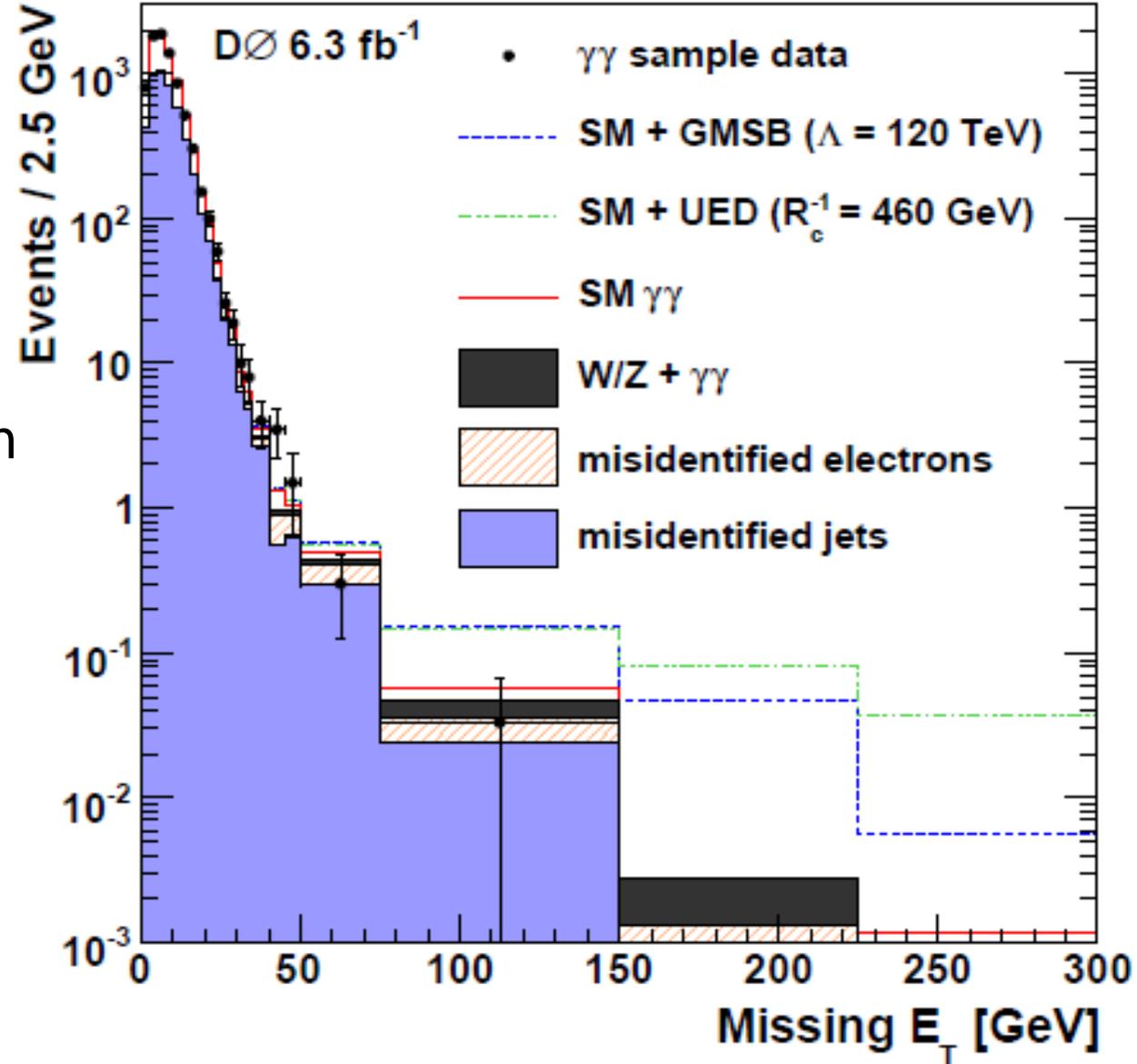
Improved photon ID

- NN e/ γ separation

Vertex confirmation from
photon pointing

Reduced systematics
using data background
control samples

Data consistent with SM



$\gamma\gamma + \text{MET}$

Much larger dataset

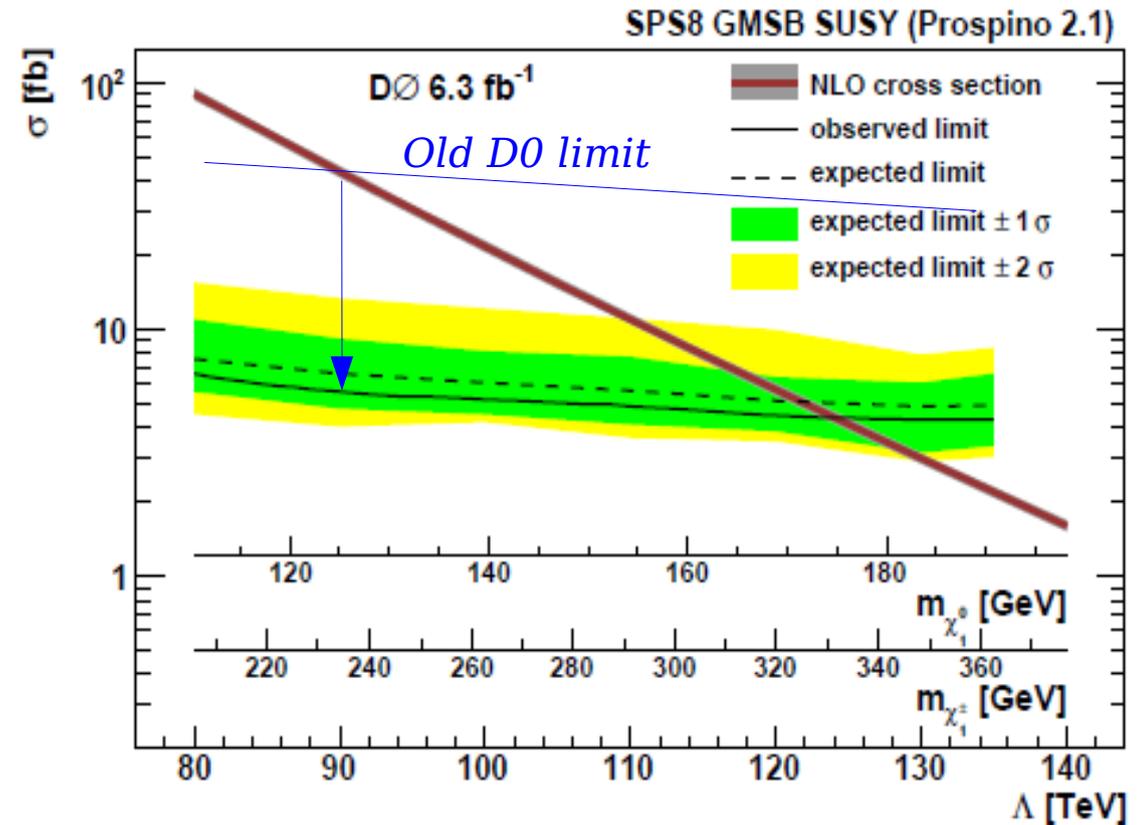
Improved photon ID

- NN e/ γ separation

Vertex confirmation from
photon pointing

Reduced systematics
using data background
control samples

Data consistent with SM



$m(\chi_1^0) < 175 \text{ GeV}$

compare w/ 125 GeV D0 1.1 fb^{-1}

149 GeV CDF 2.6 fb^{-1}

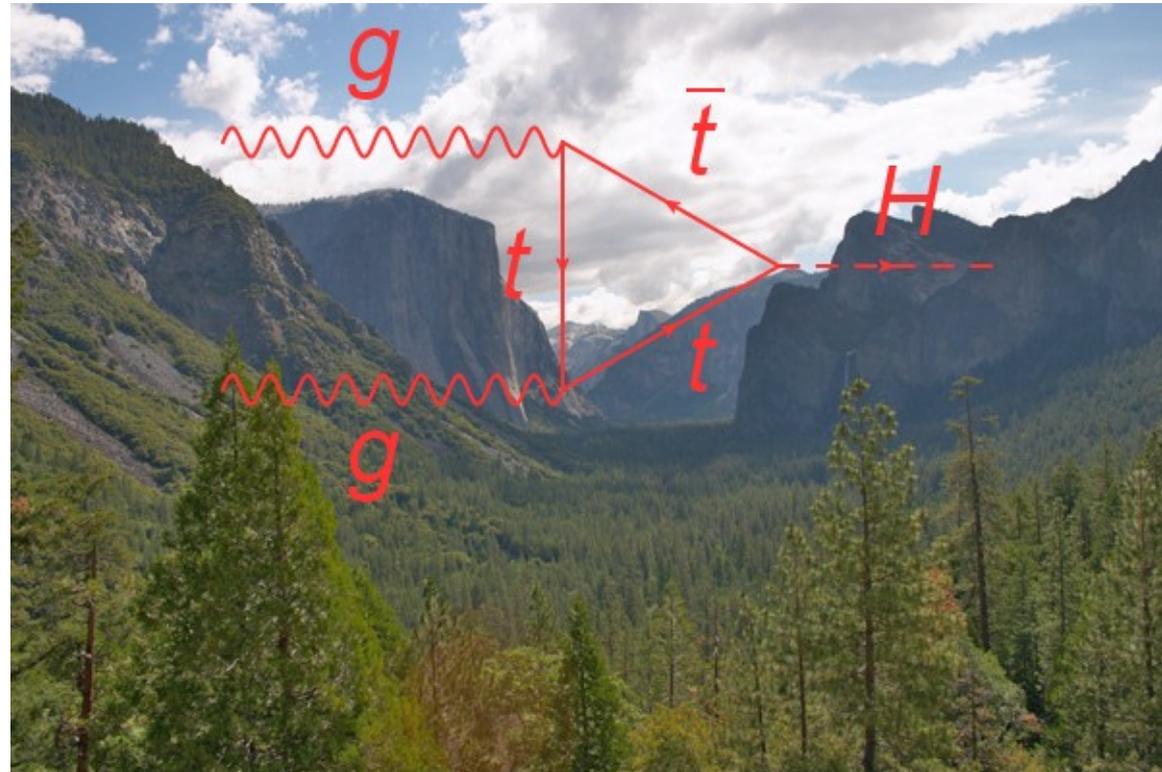
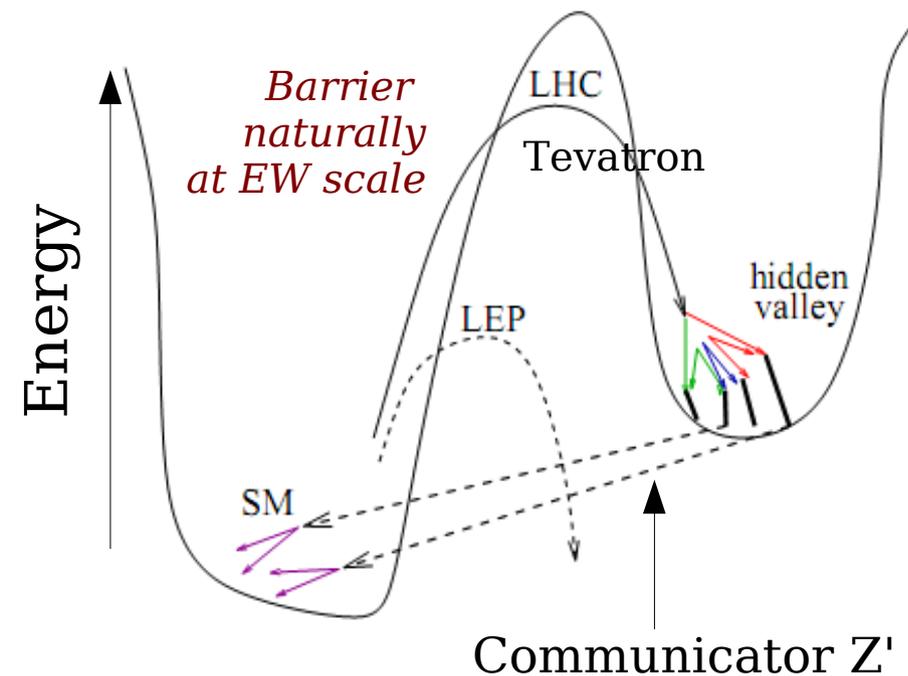
arXiv:1008.2133
Submitted to PRL

Hidden Valley

Nature doesn't have to be just $SU(3) \times SU(2) \times U(1)$!

Super-string theories naturally have additional gauge groups, but they're **weakly-coupled** to us (at low energy)

Strassler and Zurek,
Phys. Rev. Lett.
B651:374 (2007).

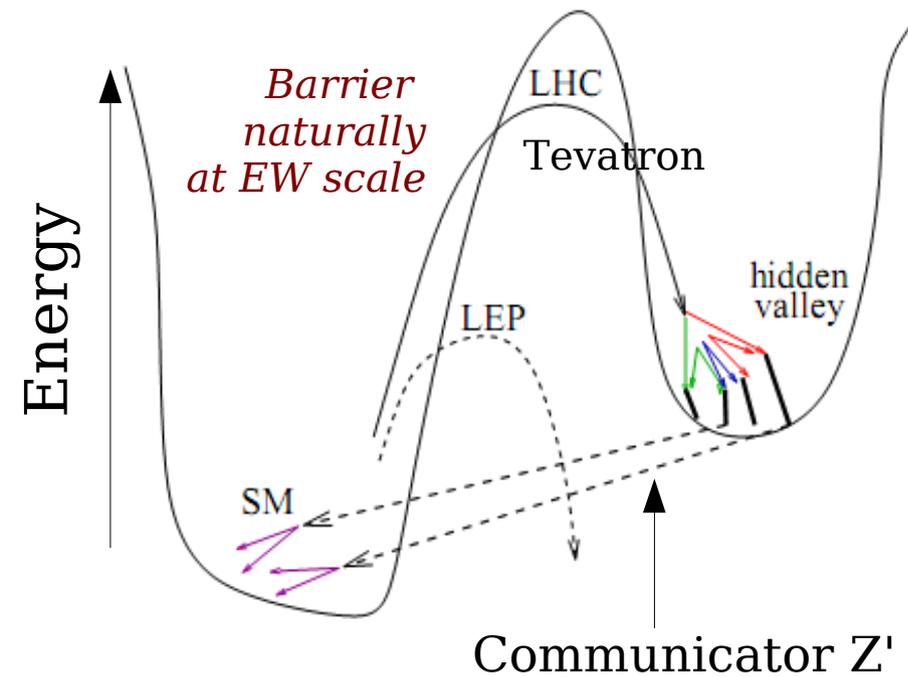


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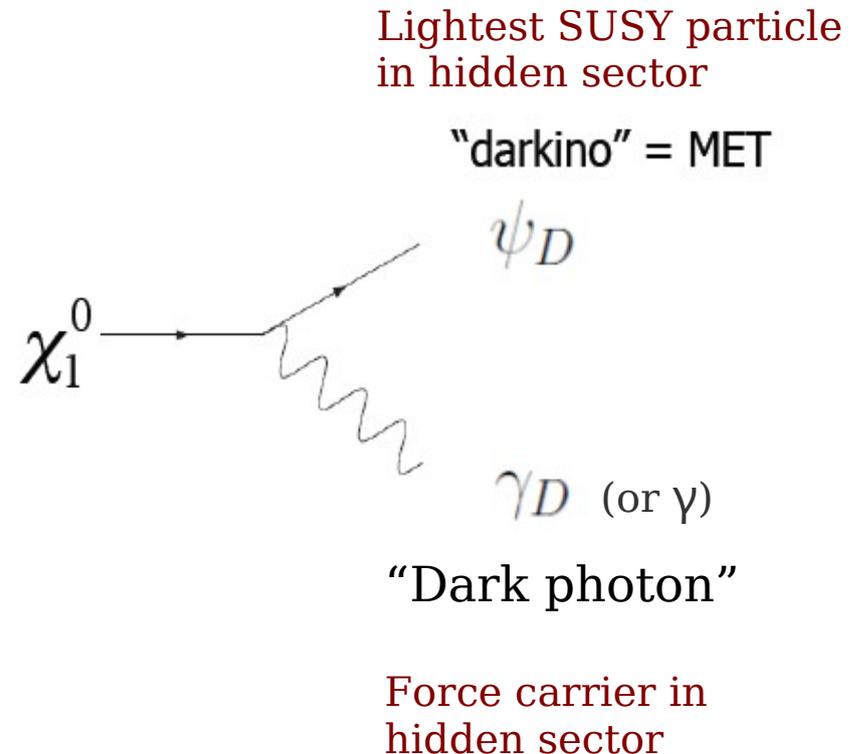
Hidden Valley

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Super-string theories naturally have additional gauge groups, but they're **weakly-coupled** to us (at low energy)

New, kinetically coupled $U(1)$

$$\mathcal{L}_{\text{gauge mix}} = -\frac{1}{2}\epsilon_1 b_{\mu\nu} A^{\mu\nu} - \frac{1}{2}\epsilon_2 b_{\mu\nu} Z^{\mu\nu}$$



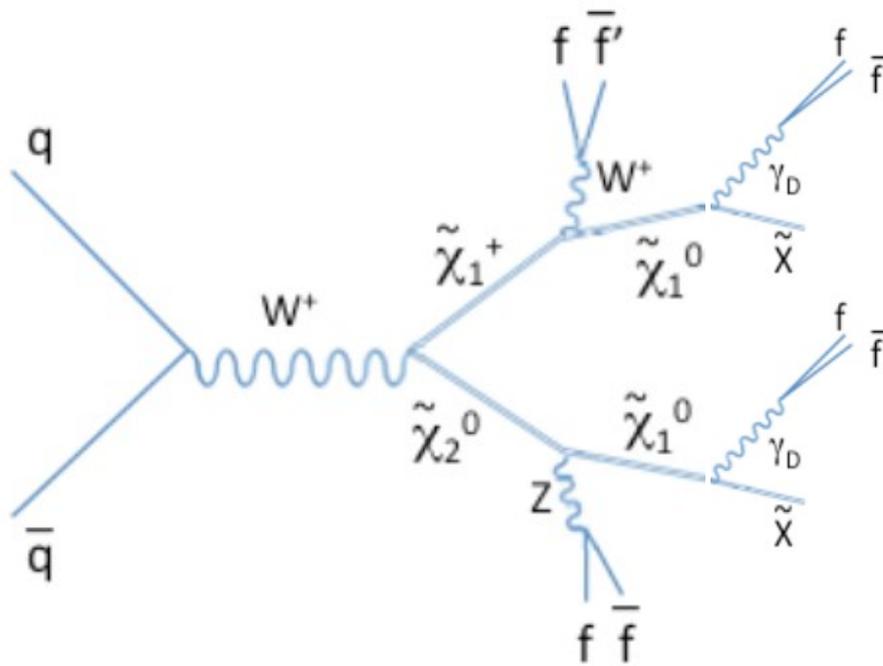
Arkani-Hamed, Finkbeiner, Slatyer, Weiner
Phys.Rev.D79:015014,2009.

Hidden Valley

Hidden-sector dramatically changes what SUSY looks like !

Example: Chargino / Neutralino production

Hidden Valley: **Neutralino decays into hidden-sector particles**



New signature!
2 dark-photons (+MET?)

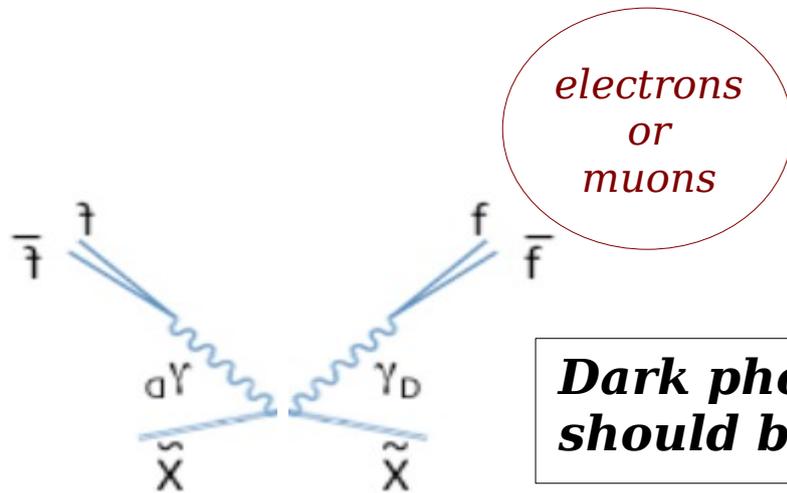
Exactly what it looks like
depends on details of
the hidden-sector

A hint from space?

Dark Matter *annihilating* in space

No excess of anti-protons seen...

Hint of $DM+DM \rightarrow e^+e^-$?

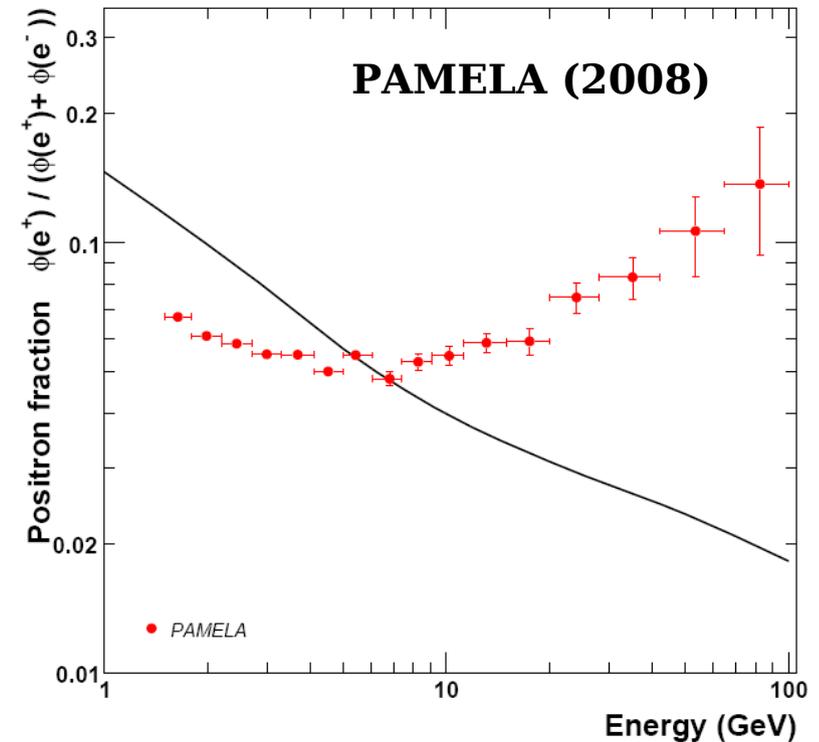


Dark photon (and darkino) should be light ($< \sim 1$ GeV)

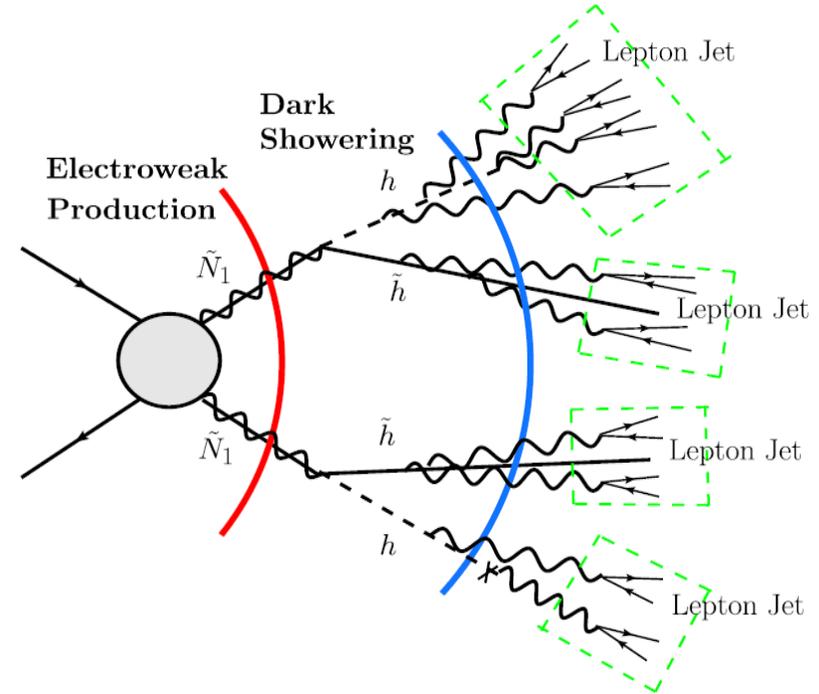
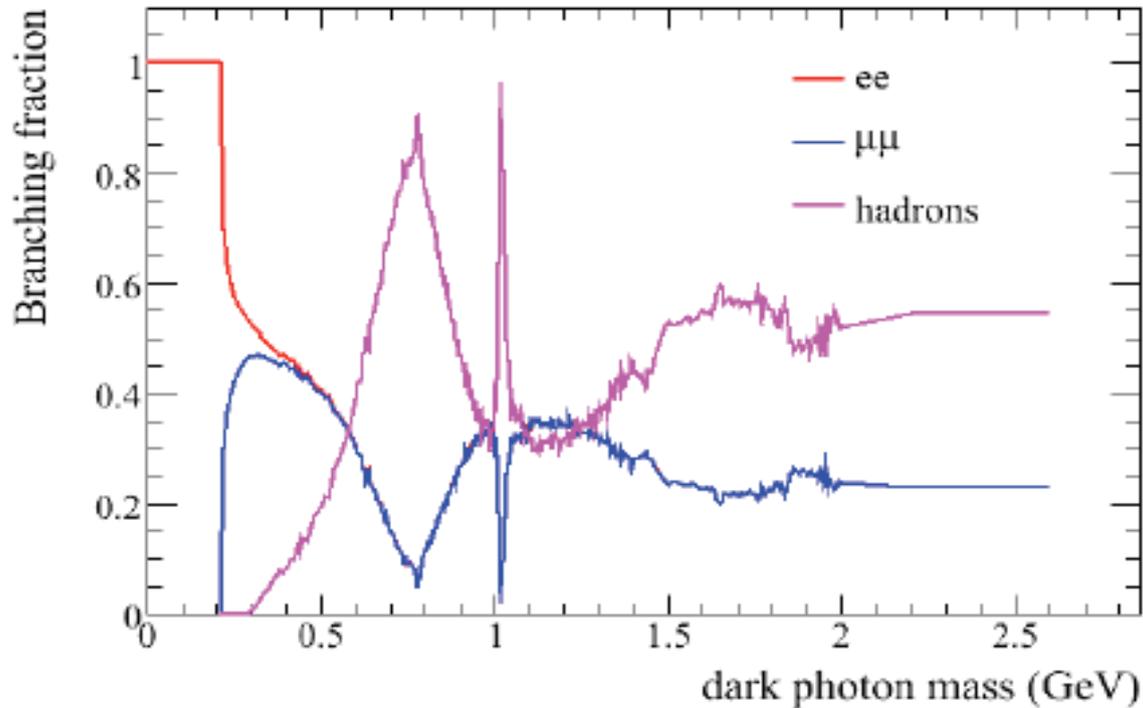
Hidden sector can explain positron excess!

(and maybe DAMA too)

D.P. Finkbeiner and N. Weiner
Phys.Rev.D **76** 083519 (2007).



“Lepton jets”



Decay is forced mostly into leptons...

γ_D is *boosted*, appears as “**lepton-jet**” (*l-jet*):

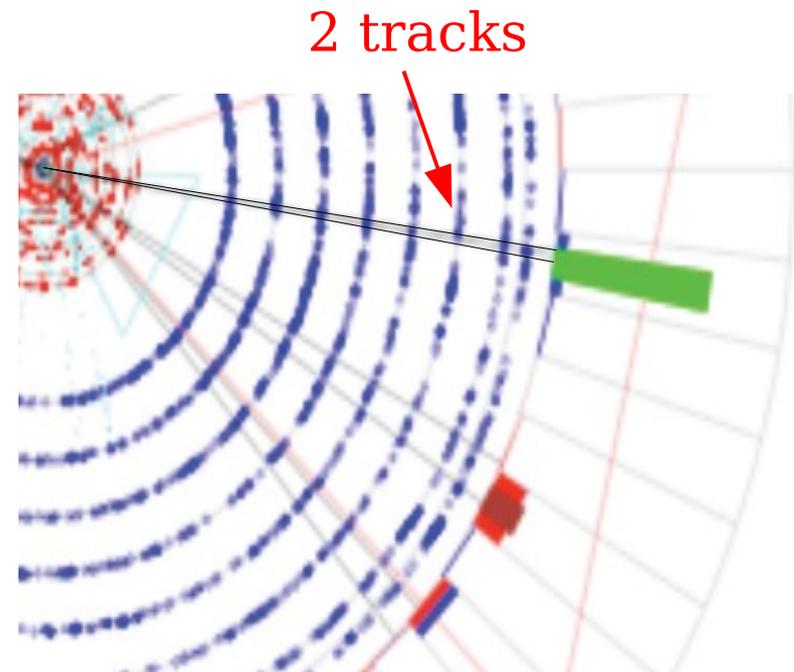
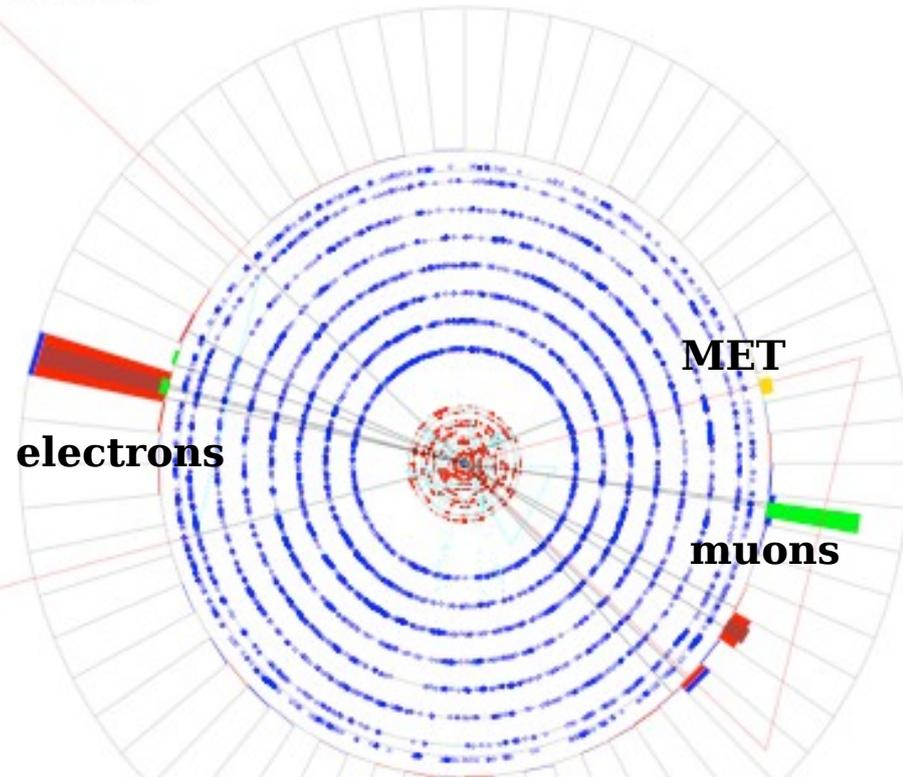
Pair (or more) of collinear e's or μ 's

Cheung, Ruderman, Wang, Yavin
JHEP 1004:116,2010.

“Lepton jets”

Run 1 Evt 271 03-Oct-2009

ET scale: 123 GeV



**Almost all previous Tevatron analyses
would throw out this event...**

Leptons fail standard track isolation !

L-jet Identification

“Electron l-jet seed”

EM cluster, $p_T > 15$ GeV

Matched to $p_T > 10$ GeV track

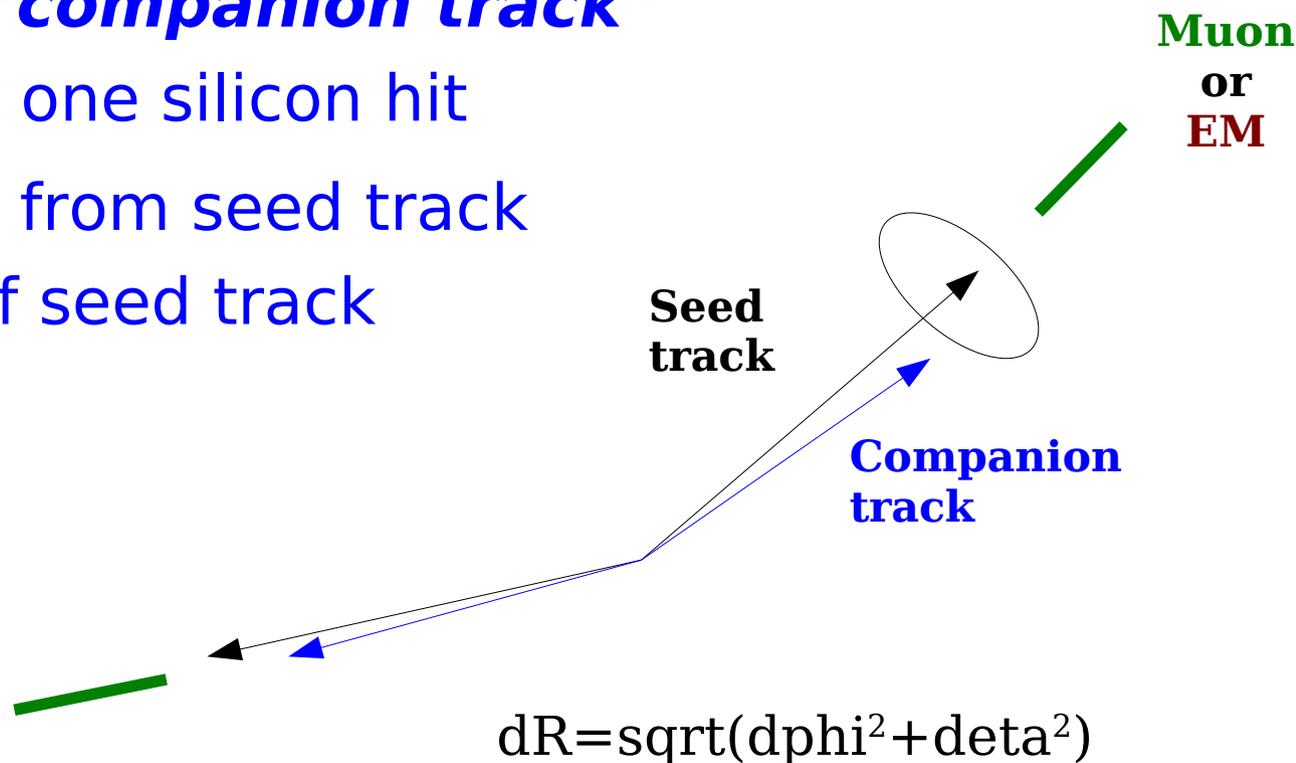
“Muon l-jet seed”

Track in muon system

Matched to $p_T > 10$ GeV track

Each must have a “companion track”

- $p_T > 4$ GeV, at least one silicon hit
- $dR < 0.2$, $|dz| < 1$ cm from seed track
- Opposite charge of seed track

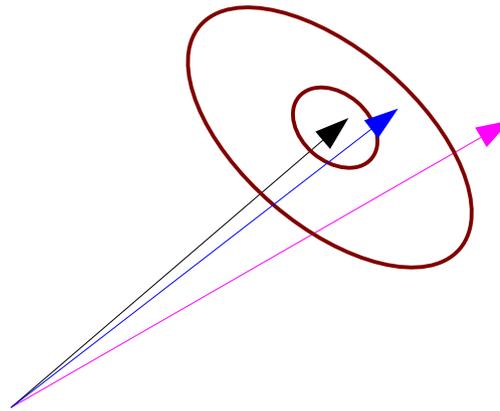


L-jet Isolation

Need isolation to separate l-jet from multi-jet background

But keep isolation loose enough to not kill possible signals!

- May have many more tracks, be wider from radiation, etc...



Track isolation: $p_T < 2 \text{ GeV}$ other than companion, in $0.2 < dR < 0.4$

Calorimeter isolation:

Cuts are functions of l-jet p_T - don't bias MET measurement

Two L-jet Data Sample

MET distribution for 2 isolated L-jets
(not μ corrected - calorimeter only)

Background determined from *non-isolated data scaled to data for MET < 15 GeV*

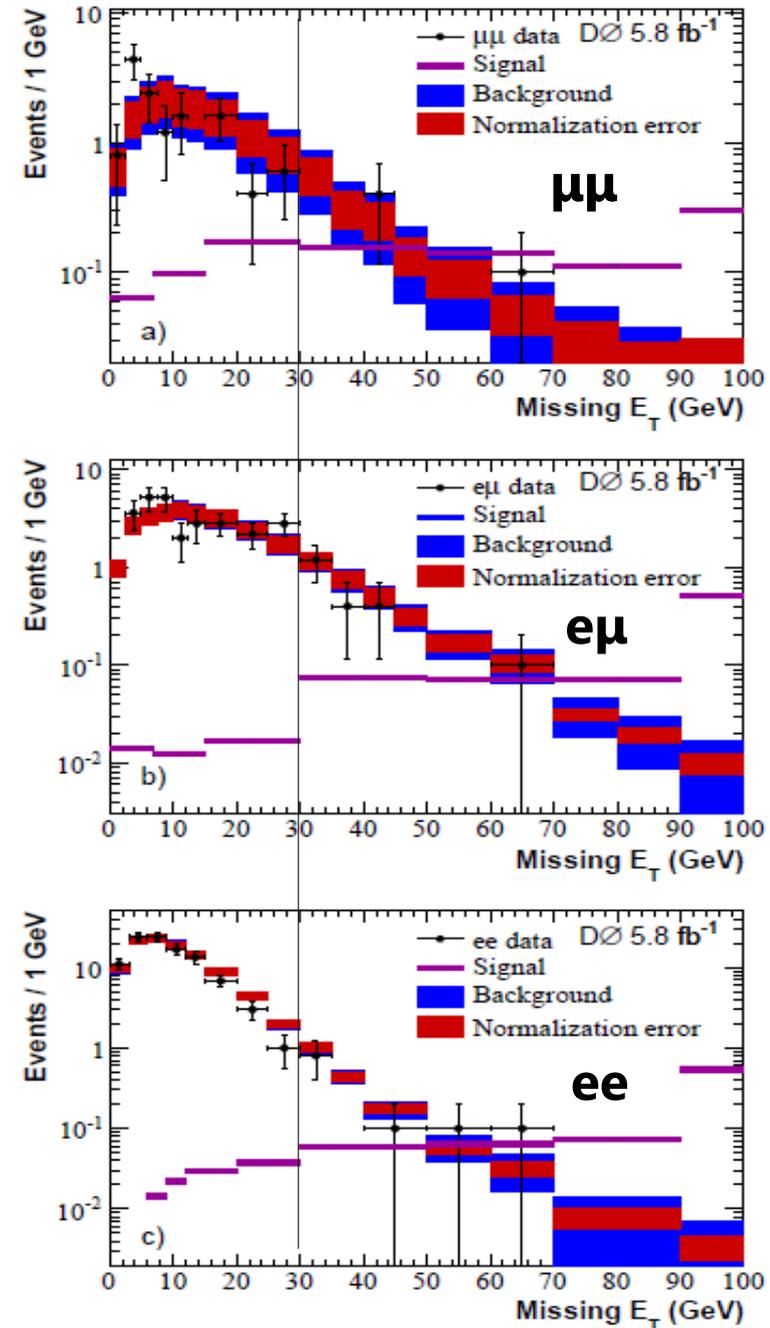
- Normalization uncertainty from statistics

Systematics on background shape

- change in the MET shape when just one L-jet is non-isolated

Require MET > 30 GeV

No excess observed at high MET



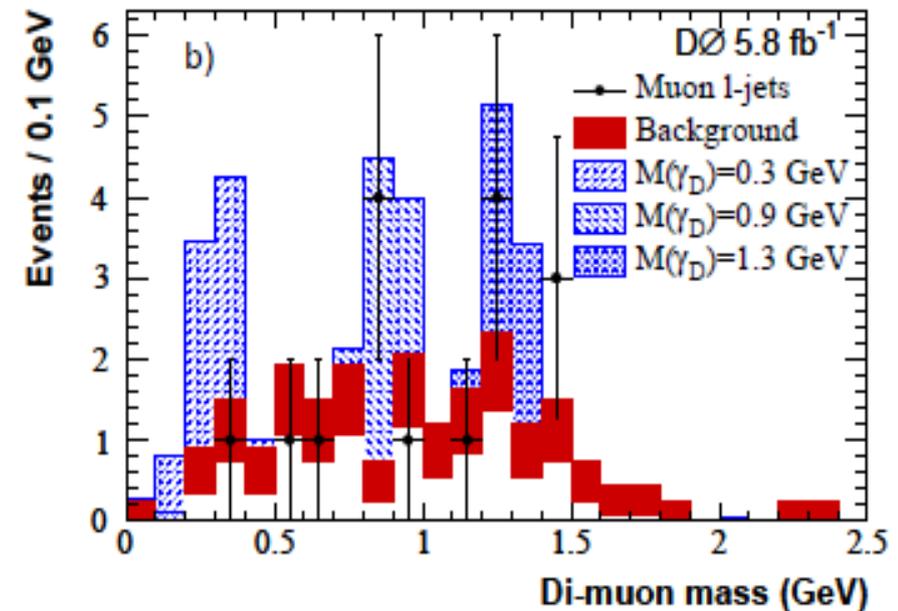
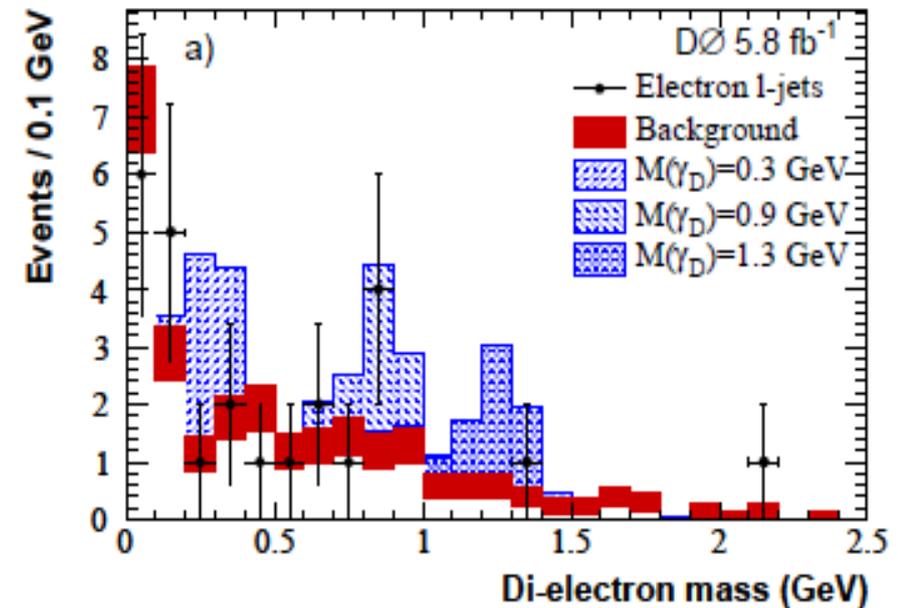
Resonance Search

For events with 2 isolated l-jets and $MET > 30$ GeV, look for resonance in track / companion track mass

Background estimated from isolated 2 l-jet sample with $MET < 20$ GeV

No significant peak observed

$M(\gamma_D)$ (GeV)	B_e/B_μ	$\Delta M(l\text{-jet})(\text{GeV})$	Eff. $ee/\mu\mu(\%)$
0.15	1.00/0.00	0.0–0.3	81/–
0.3	0.53/0.47	0.1–0.4	82/88
0.5	0.40/0.40	0.3–0.6	81/89
0.7	0.15/0.15	0.4–0.8	85/89
0.9	0.27/0.27	0.6–1.1	82/91
1.3	0.31/0.31	0.9–1.4	72/79
1.7	0.22/0.22	1.0–1.8	73/76
2.0	0.24/0.24	1.3–2.2	73/83



$\Upsilon_D + \Upsilon_D + \text{MET}$ Results

Limits with CL_s method

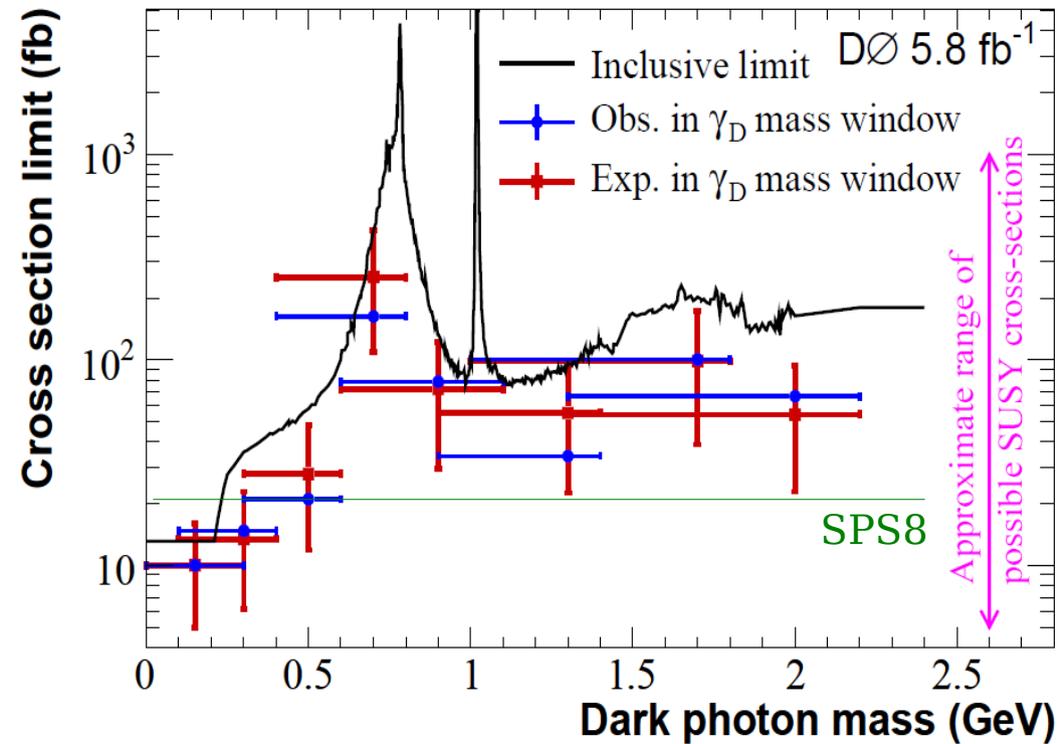
Systematics

- Signal efficiency, 20%
- Background, 20-50%
- Luminosity, 6.1%

Rules out “SPS8” for decays to jets for low γ_D masses

Would rule out other SUSY points with lighter chargino / neutralino, or strong production

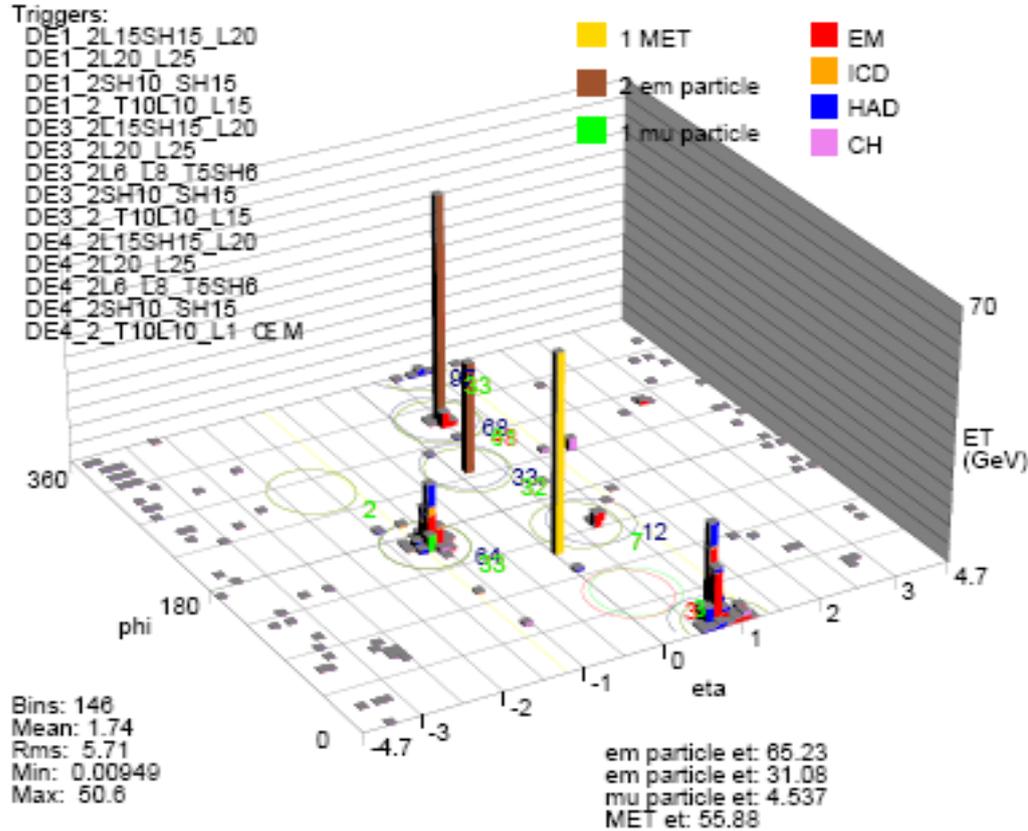
arXiv:1008.3356
Submitted to PRL



Chan.	\mathcal{R}_f	N_{obs}	N_{pred}	$\mathcal{A}(\%)$	$\epsilon(\%)$	\mathcal{B}	$\sigma_{95\%} \times \mathcal{B}$, fb	
							obs.	pred.
$\mu\mu$	0.33	3	8.6 ± 4.5	50	12	\mathcal{B}_μ^2	20	35_{-21}^{+26}
$e\mu$	0.37	11	17.5 ± 4.2	53	15	$2\mathcal{B}_e\mathcal{B}_\mu$	19	30_{-18}^{+19}
ee	0.04	7	10.2 ± 1.7	45	20	\mathcal{B}_e^2	13	19_{-9}^{+11}

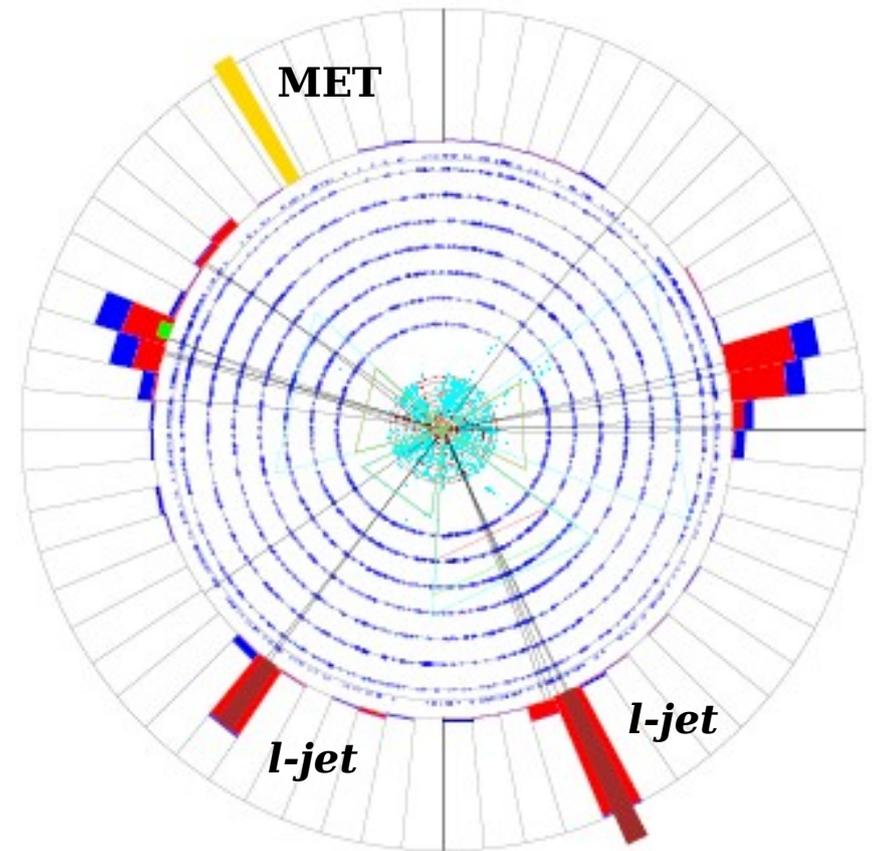
Two electron l-jets, two jets, large MET

Run 248074 Evt 24810582 Wed Dec 17 03:49:03 2008



Run 248074 Evt 24810582 Wed Dec 17 03:49:03 2008

ET scale: 52 GeV



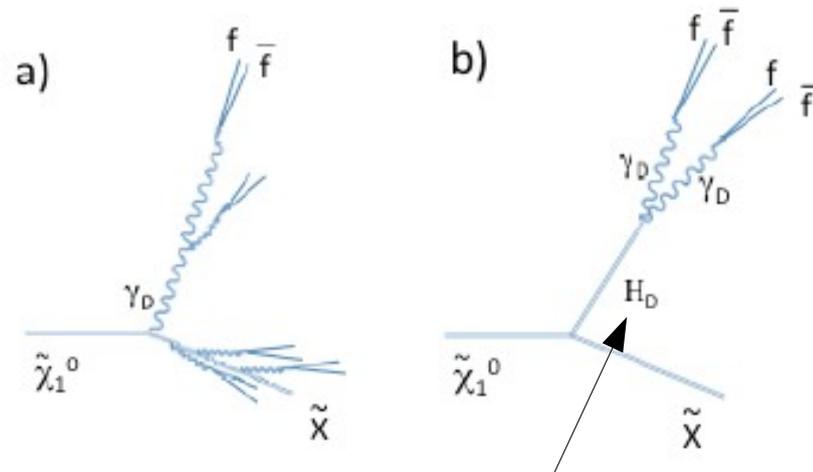
An exciting and interesting event!

More complicated dark sector

Studied using MC simulation only

a) Additional dark radiation / showers

- Adds additional tracks, hadronic E
- Raising dark coupling from $0 \rightarrow 0.3$ decreases efficiency by up to 20%

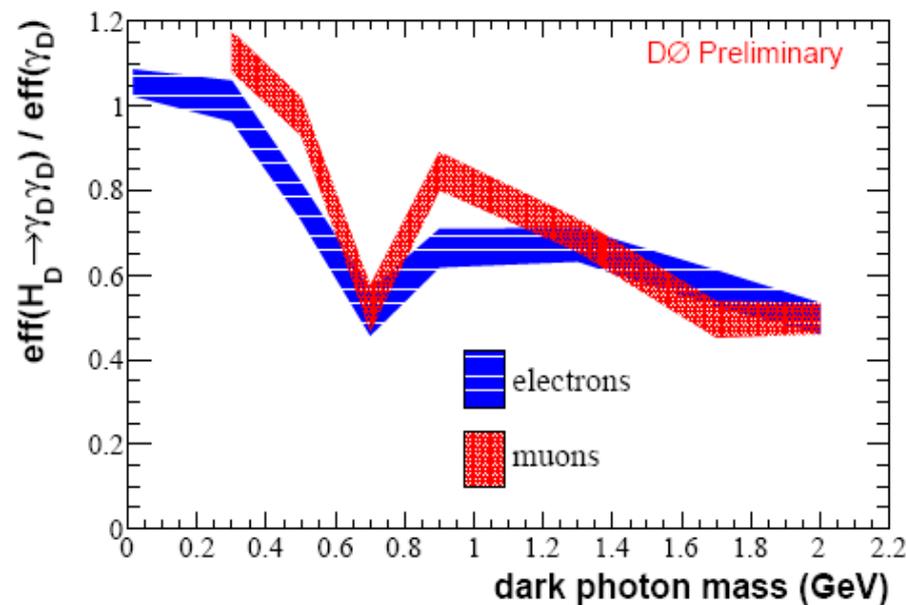


$m(\gamma_D)$	0.15	0.3	0.5	0.7	0.9	1.3	1.7	2.0
$m(H_D)$	1.2	1.2	1.2	1.6	2.0	3.0	4.0	4.5

b) Decays to dark Higgs

- Gives softer leptons
- Up to 50% lower efficiency, for large dark photon mass

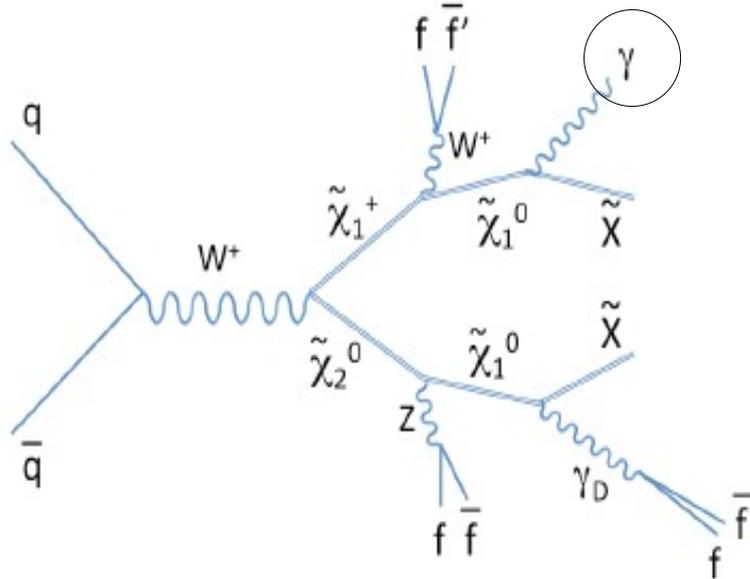
Efficiency still good for more complicated / realistic hidden-sector dynamics (*by design!*)



SUSY Hidden Valley: $\gamma_D + \gamma + \text{MET}$

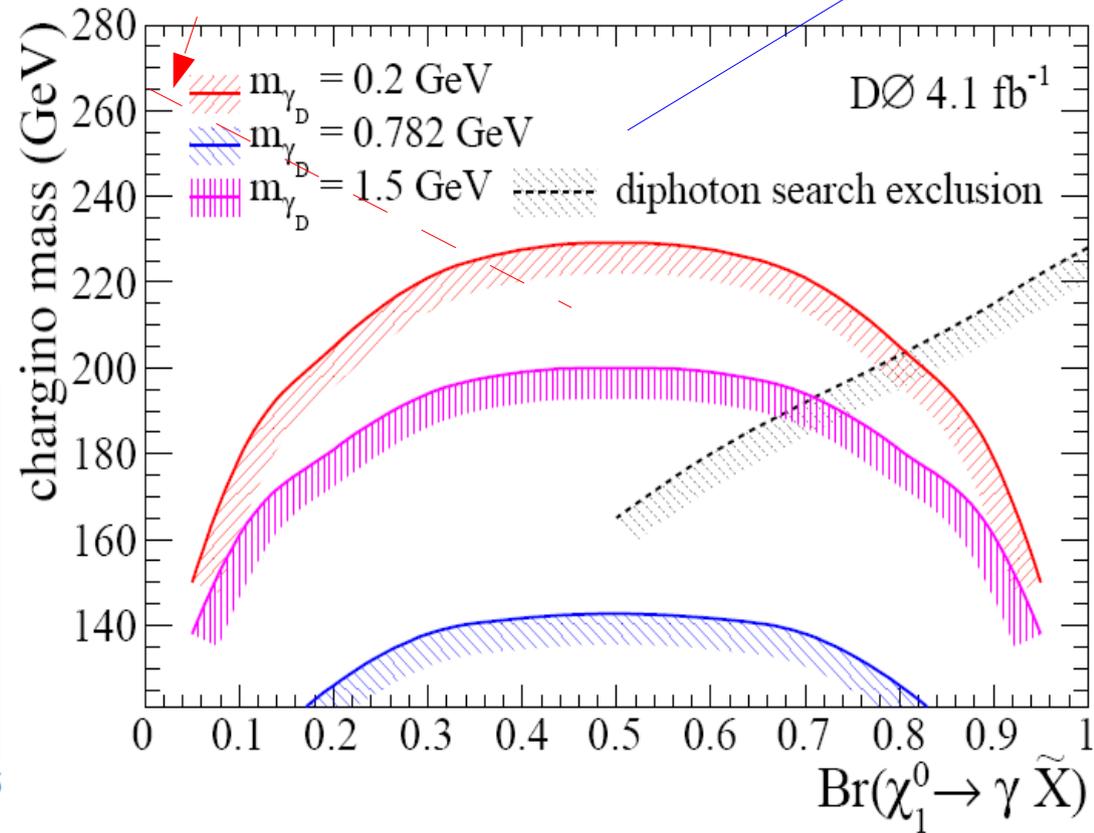
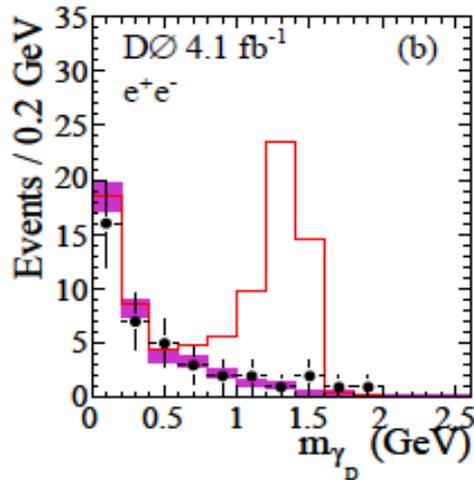
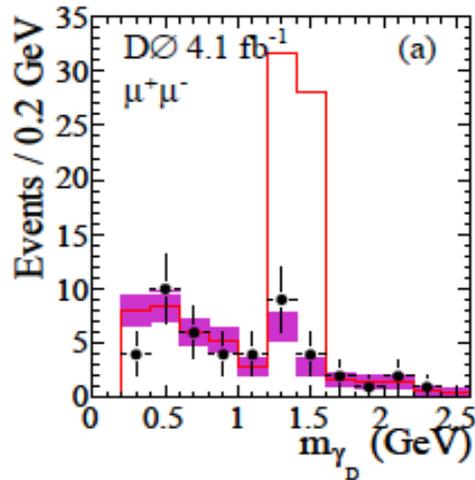
Also searched previously for
in-between case... when $BR \sim 1/2$

Phys.Rev.Lett.
103:081802,2009



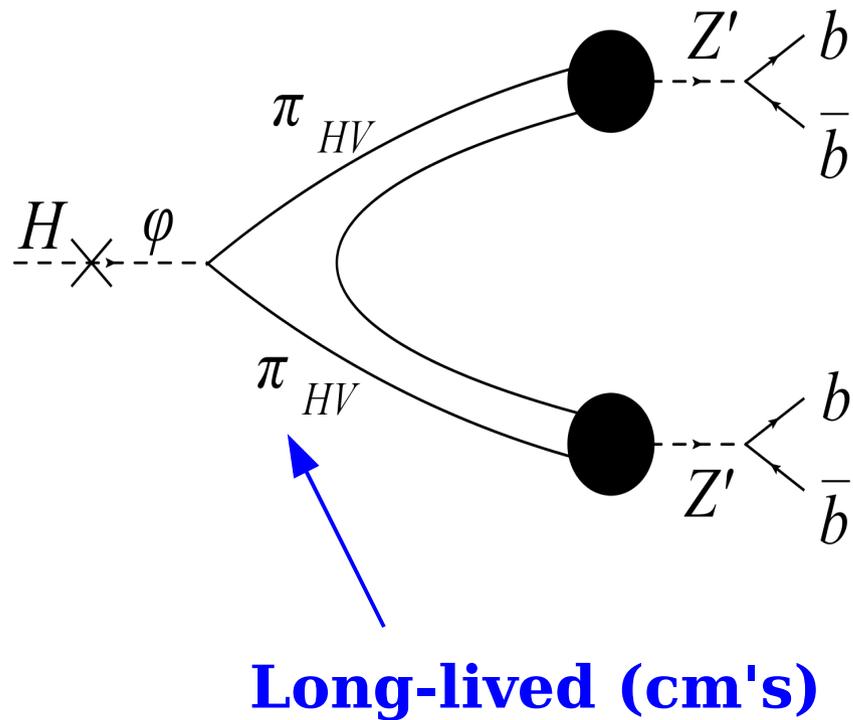
2 l-jet 5.8 fb⁻¹
result

New 6.3 fb⁻¹
2γ result

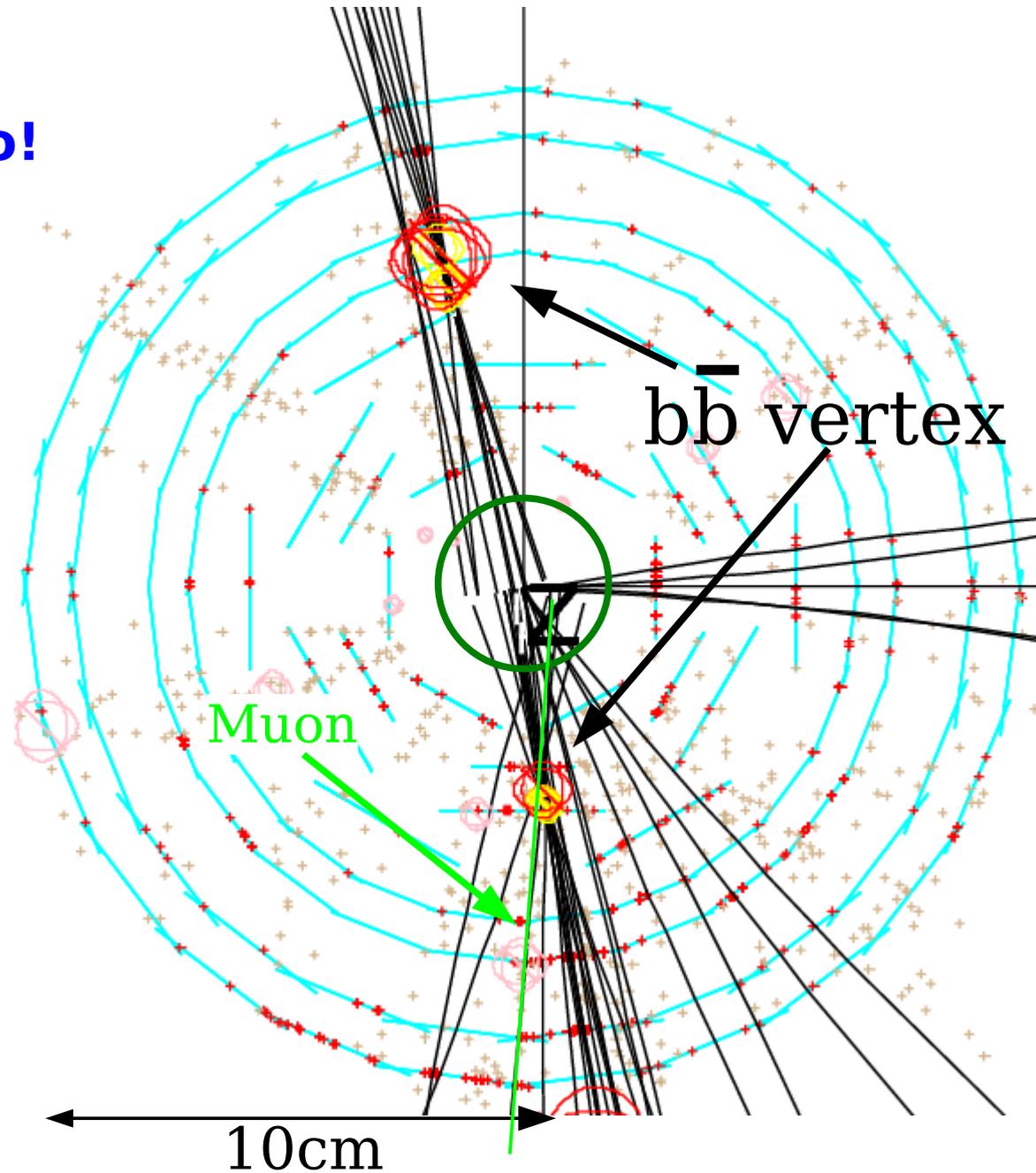


Hidden Valley Higgs

**Hidden-sector changes
what Higgs looks like too!**



**Phys.Rev.Lett.
103:071801,2009**



Quirks?

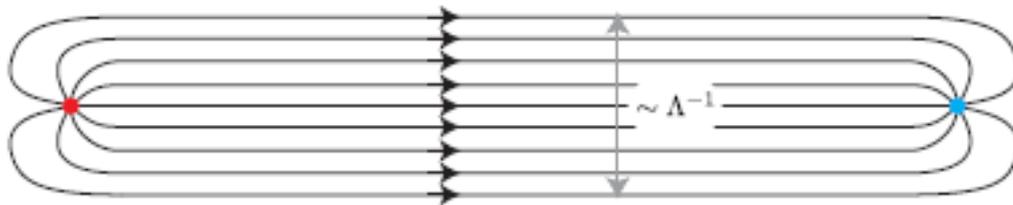
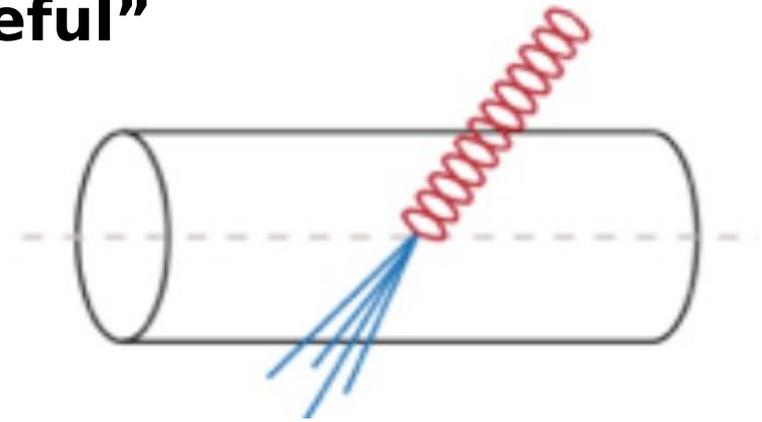
Hidden sectors don't have to be “useful”

New SU(3) group, felt only by “quirks”

- Becomes strong at scale Λ

Quirks also have SM electric charge

Very interesting phenomenology!



J. Kang, M. Luty, JHEP 0911:065 (2009)

Supernova cooling requires $M_{\text{quirk}} > \sim 10 \text{ GeV}$

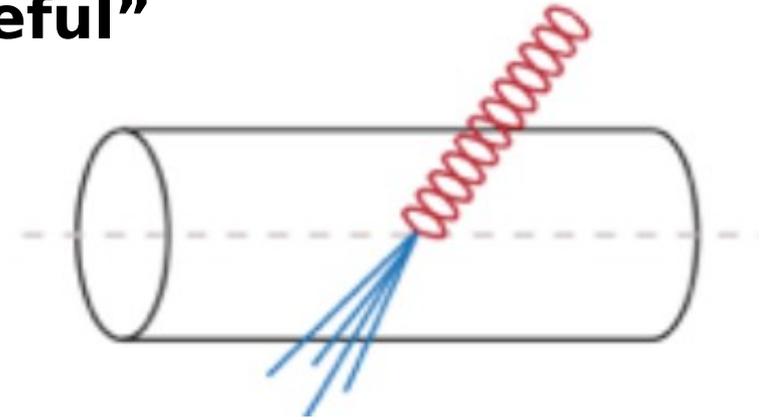
Quirks?

Hidden sectors don't have to be “useful”

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- Becomes strong at scale Λ

Quirks also have SM electric charge



Phenomenology at hadron colliders in case $\Lambda \ll m_Q \cong 0.1 - 1$ TeV:

- ▶ Breaking of infracolor string is exponentially suppressed due to large m_Q/Λ
- ▶ Hence quirks stay connected by the string, like a rubber band that can stretch macroscopically
 - $100 \text{ eV} < \Lambda < \text{keV}$: macroscopic strings: anomalous tracks
 - $100 \text{ keV} < \Lambda < \text{MeV}$: mesoscopic strings: behaves as one particle ← Focus on this case
 - $100 \text{ MeV} < \Lambda < m$: microscopic strings: annihilate, hadronic fireball

$$L \simeq \frac{m_Q}{\Lambda^2} \simeq 1 \mu\text{m} \left(\frac{m_Q}{100 \text{ GeV}} \right) \left(\frac{\Lambda}{100 \text{ keV}} \right)^{-2}$$

J. Kang, M. Luty, JHEP 0911:065 (2009)

Quirky Signature

Mesoscopic scenario

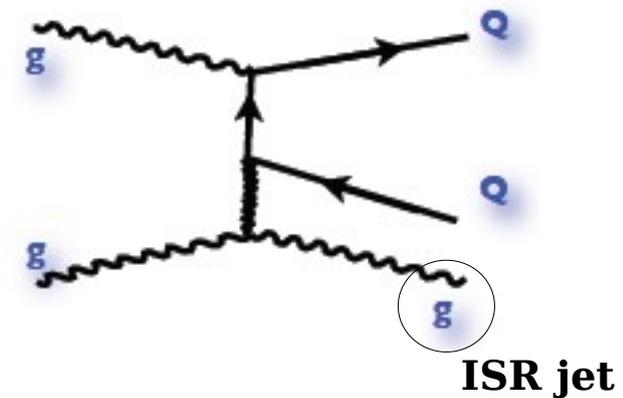
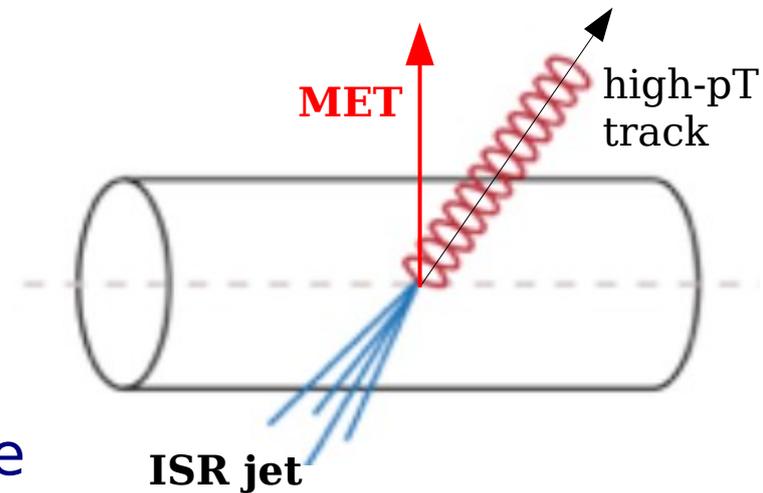
- String is from atomic sizes to \sim microns

Quirk-pair looks like a single, slow particle
Isolated track with very large p_T and dE/dx

Too slow to reach muon system in time

Require ISR jet to give boost and trigger

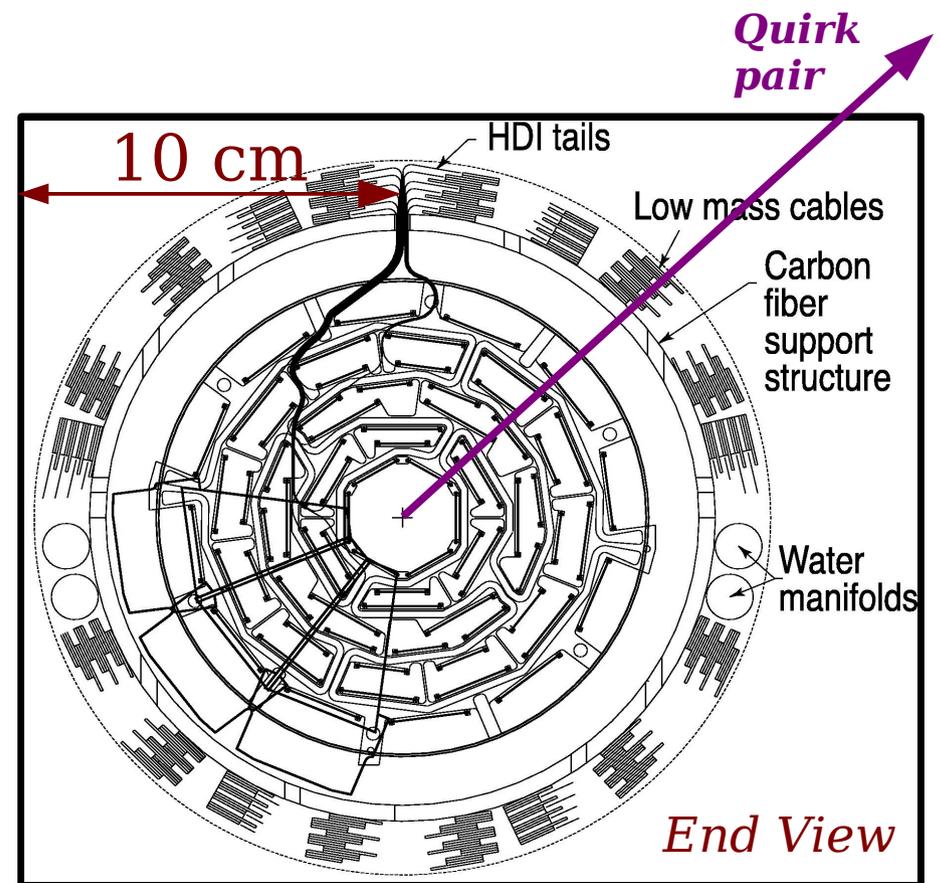
Jet + MET + isolated high- p_T track with large dE/dx
New signature!



dE/dx of quirk pair signal

dE/dx measured in silicon tracking detector

Integrate Bethe-Block ionization along path length of each quirk within silicon layers



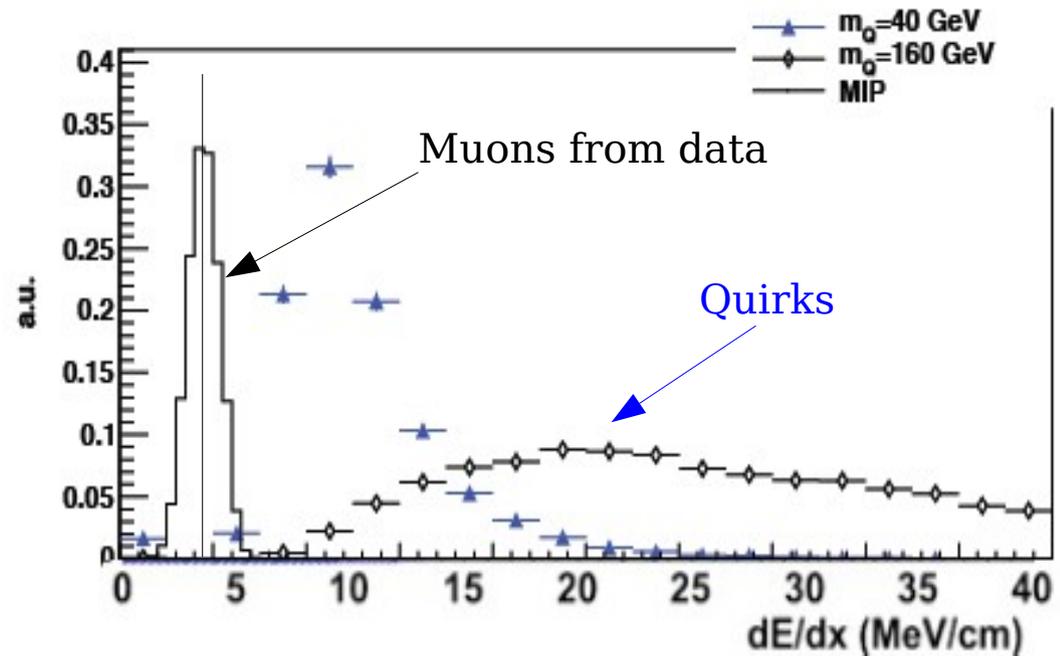
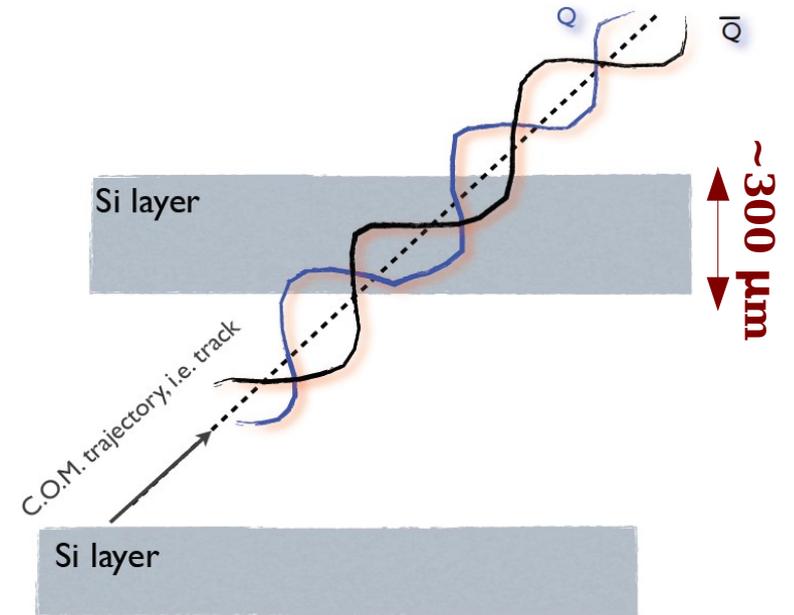
dE/dx of quirk pair signal

dE/dx measured in silicon tracking detector

Integrate Bethe-Block ionization along path length of each quirk within silicon layers

Smear dE/dx with resolution and noise measured from MIPs (muons) in data

dE/dx depends on M_Q



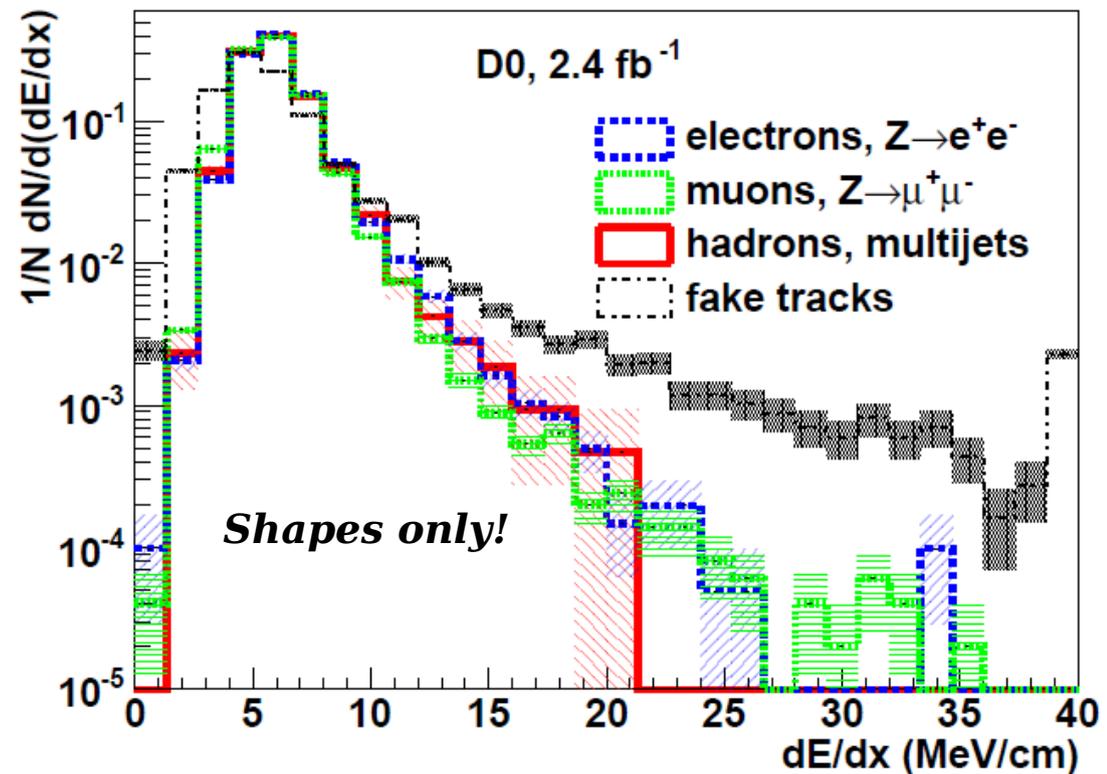
Understanding the quirky backgrounds

All backgrounds are determined from data

dE/dx shapes from leptons and hadrons (in jets) similar

- Difference taken as systematic uncertainty

Normalized to data at low dE/dx



Fake tracks selected with no matching hits in fiber-tracker

- Wider dE/dx shape from overlaps and wrong crossing angle

Fortunately, very few isolated fake tracks with fiber-tracker hits

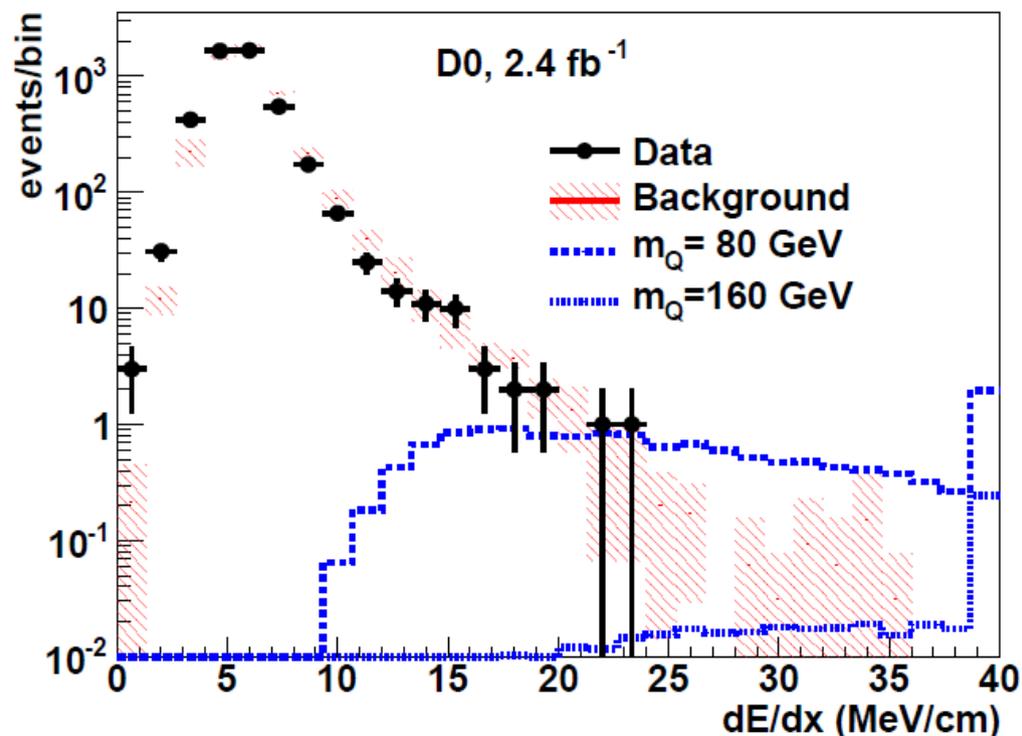
- Background conservatively ignored for limit-setting

Quirky Results

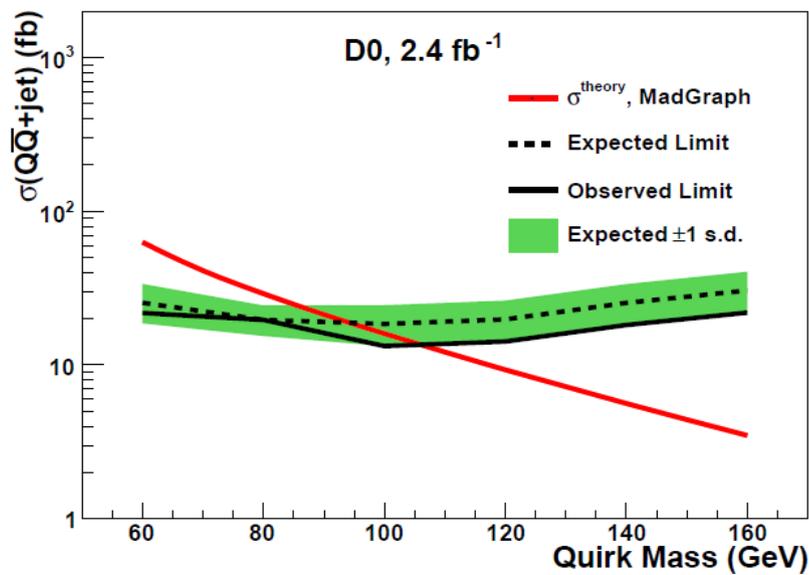
First search for Quirks!

No excess at high dE/dx

$M_Q > 107 \text{ GeV}$



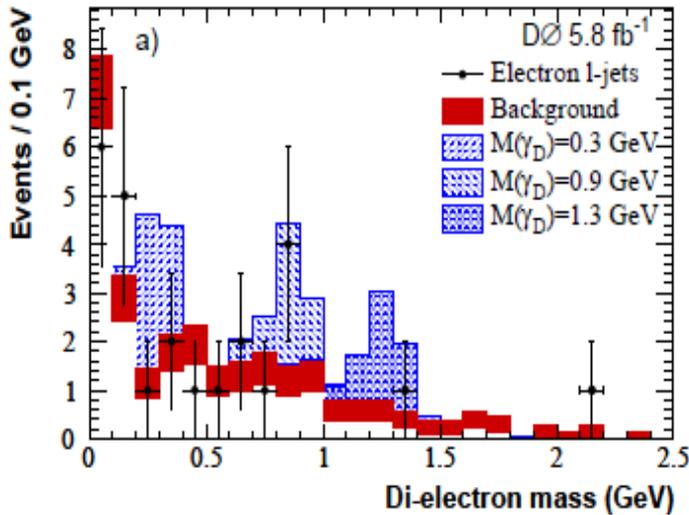
arXiv:1008.3547
Submitted to PRL



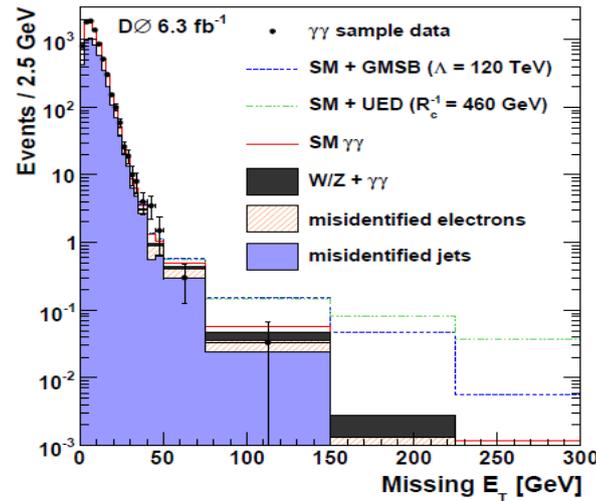
$M_Q \text{ (GeV)}$	$dE/dx \text{ cut (MeV/cm)}$	N_{data}	$N_{\text{bkg}} \pm \text{syst}$	Efficiency \pm syst (%)	$\sigma \text{ (fb)}$	Limit obs.(exp.) (fb)
60	19	4	5 ± 1	11 ± 2.0	63	22 (25)
80	21	2	1.9 ± 0.8	9.9 ± 2.1	29	20 (20)
100	24	0	0.9 ± 0.4	9.2 ± 1.9	16	13 (18)
120	24	0	0.9 ± 0.4	8.4 ± 1.7	9.3	14 (19)
140	24	0	0.9 ± 0.4	6.9 ± 1.4	5.6	18 (25)
160	24	0	0.9 ± 0.4	5.6 ± 1.1	3.4	22 (31)

Conclusions

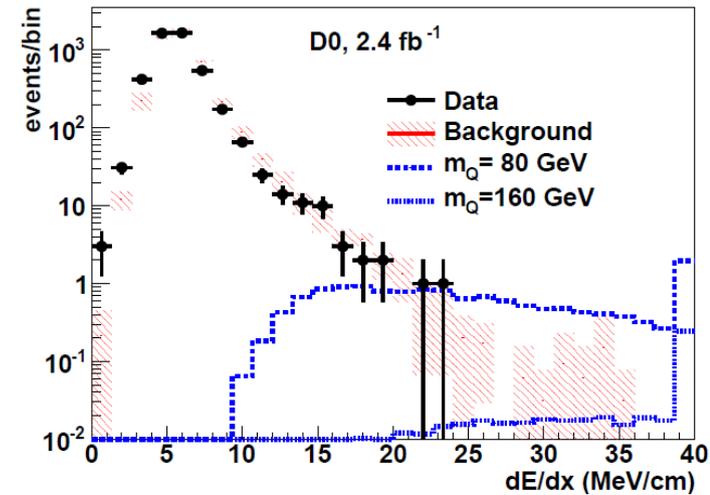
3 searches submitted to PRL in August!
(Einstein took all of 1905!)



SUSY with two
dark-photons

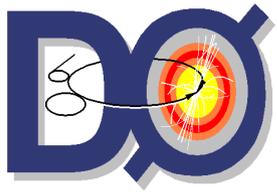


SUSY with two
light-photons



Quirks

**Still no evidence for new physics...
but we're leaving no stone unturned!**



Backup

Tracking efficiency vs. dR

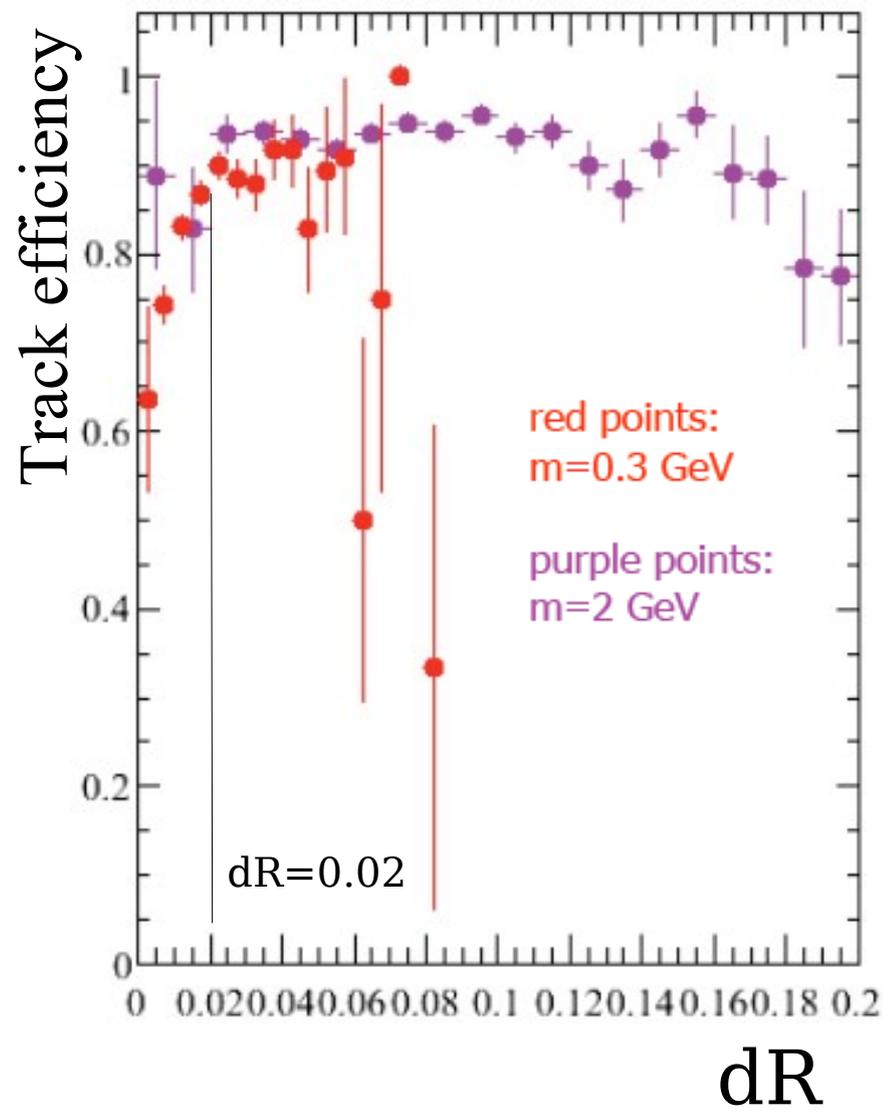
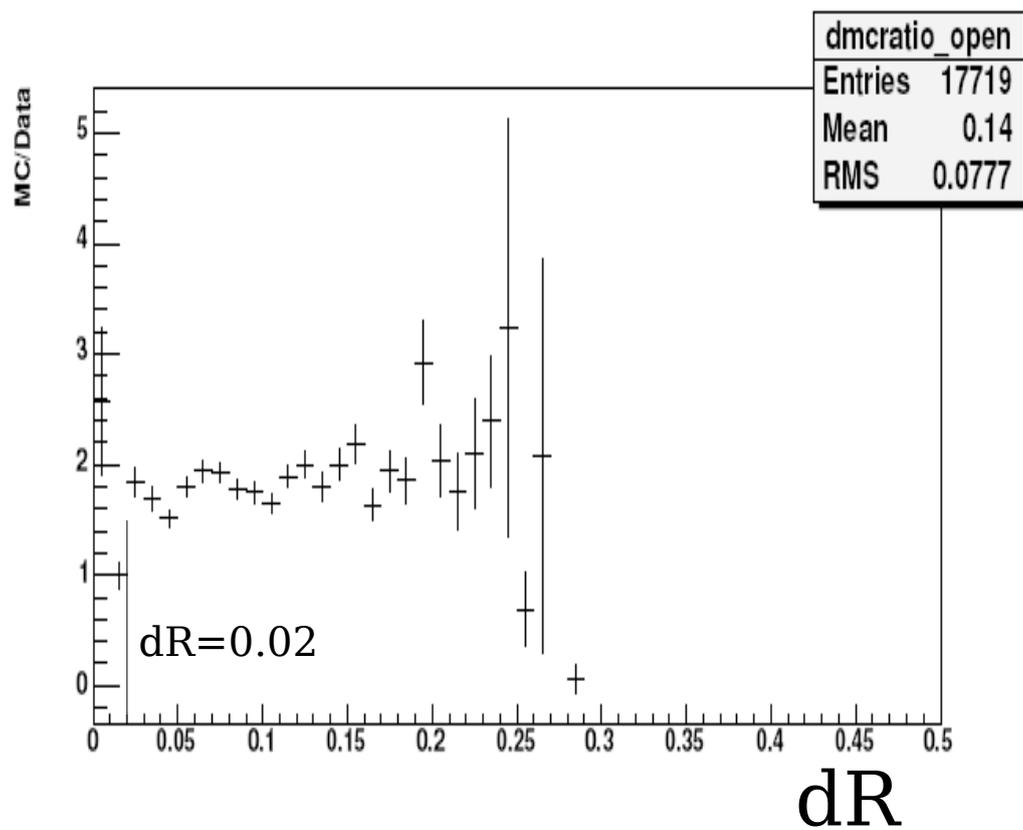


Figure 19: Ratio of Monte Carlo to data as a function of reconstructed K_s opening angle.

Previous Searches (GMSB context)

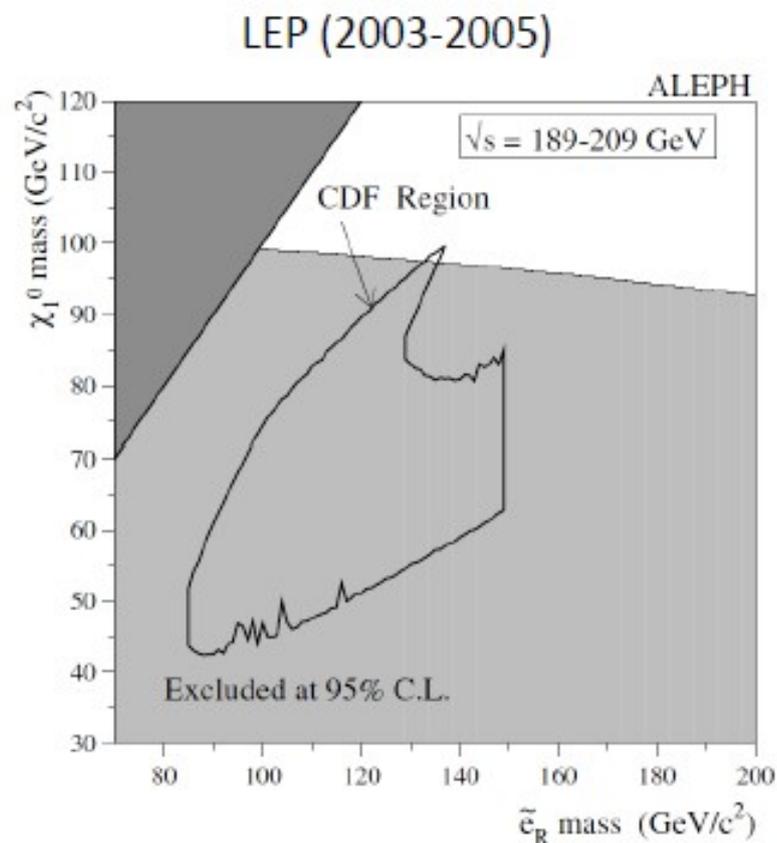


Fig. 8. The excluded region in the neutralino-selectron mass plane at 95% C.L. for the process $e^+e^- \rightarrow \chi_1^0\chi_1^0 \rightarrow \tilde{G}\tilde{G}\gamma\gamma$ and a pure bino neutralino (light shaded area). Overlaid is the region favoured by the CDF event [29] assuming the reaction $q\bar{q} \rightarrow \tilde{e}_R\tilde{e}_R \rightarrow ee\chi_1^0\chi_1^0 \rightarrow ee\tilde{G}\tilde{G}\gamma\gamma$ [30]. The dark shaded region corresponds to $M_{\tilde{e}_R} < M_{\chi_1^0}$

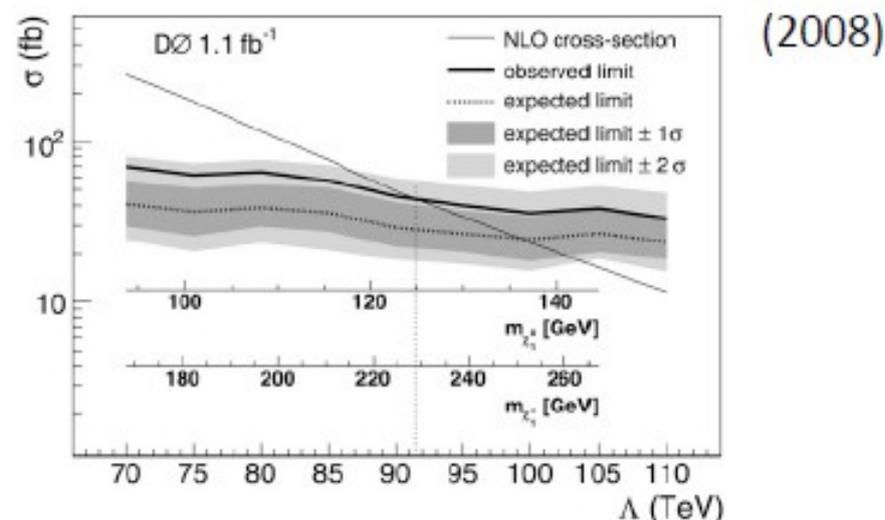
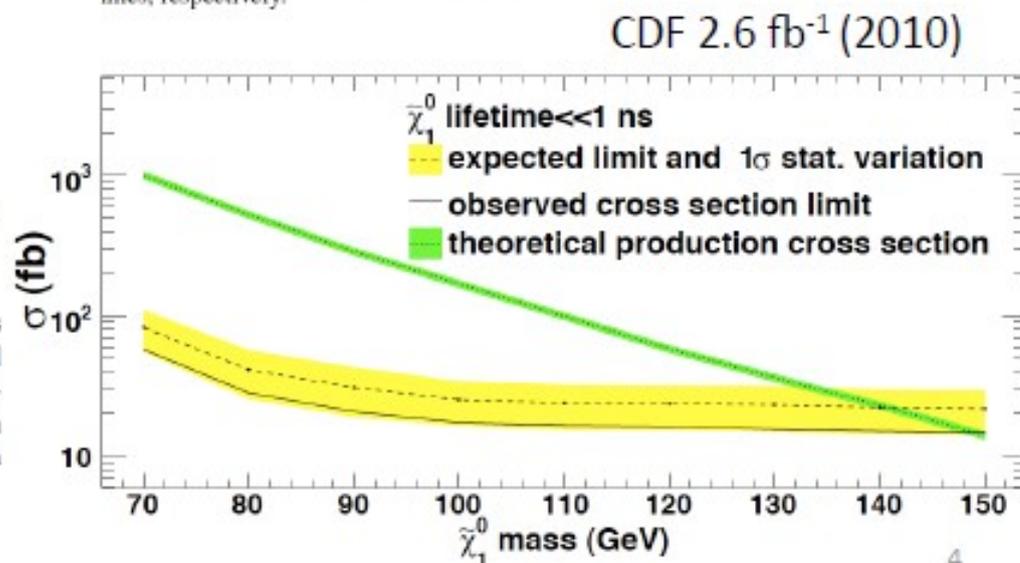


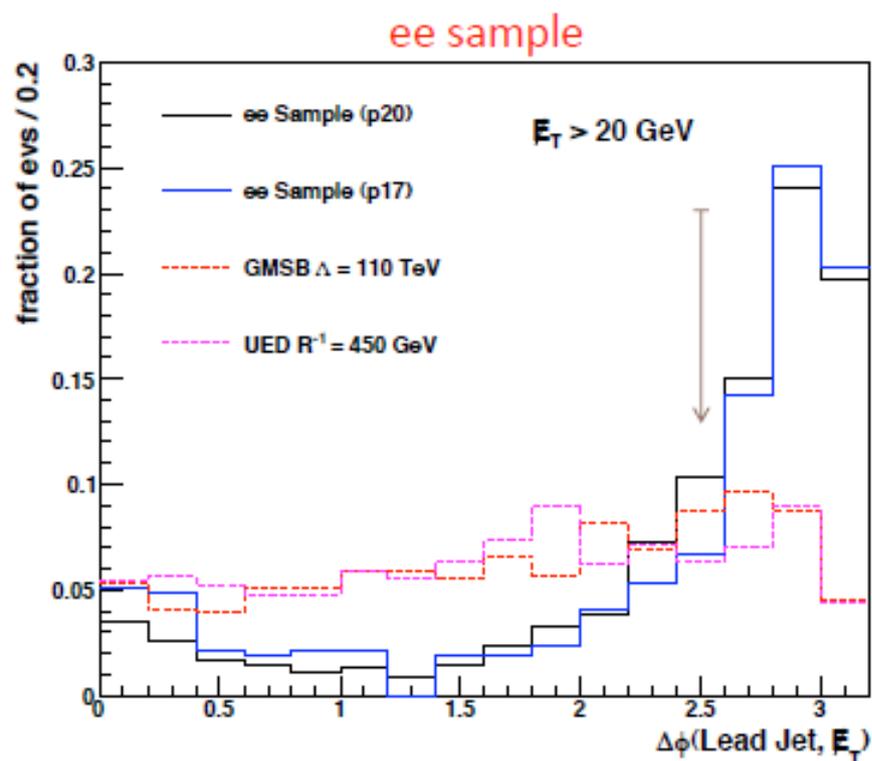
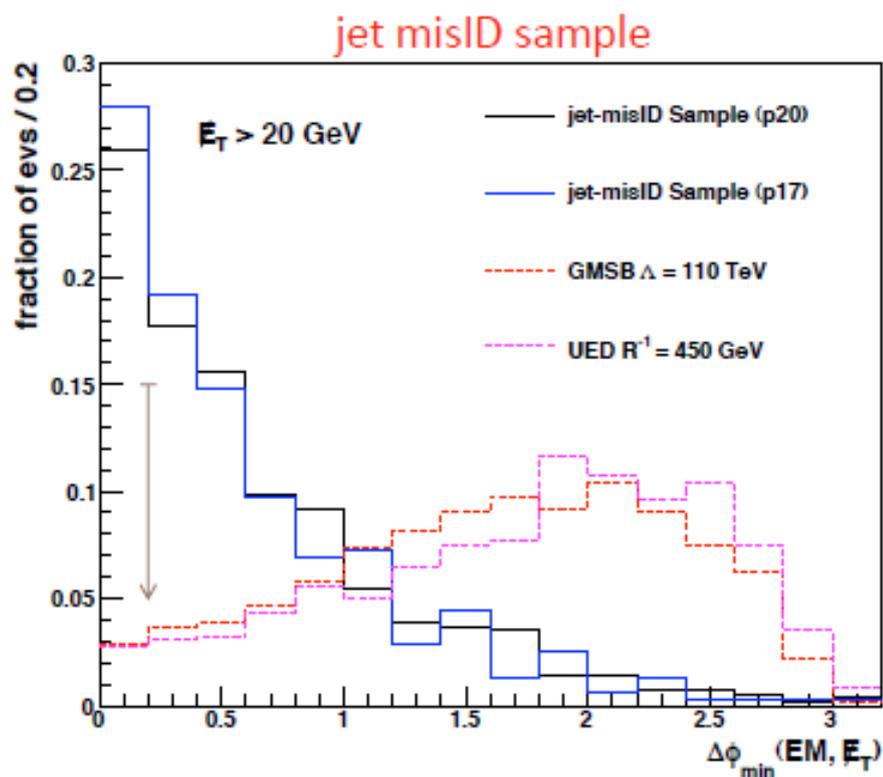
Fig. 2. Predicted cross section for the Snowmass Slope model versus Λ . The observed and expected 95% C.L. limits are shown in solid and dash-dotted lines, respectively.

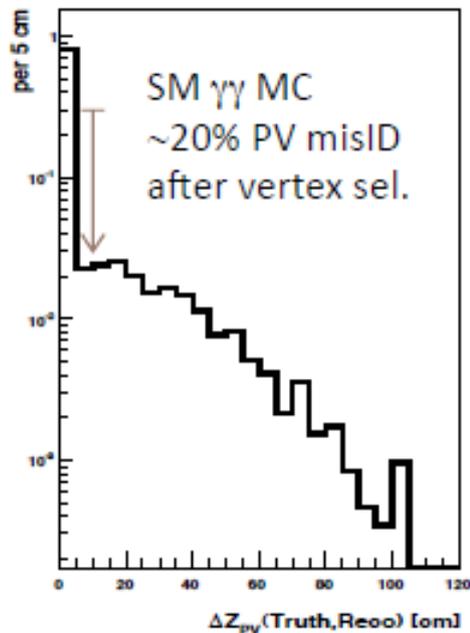


$\Delta\phi$ Requirements to Reduce MET Mismeasurements

Tendency for MET alignment with an EM cluster (primarily trailing EM cluster).
MET in signal events often well separated from both EM clusters.

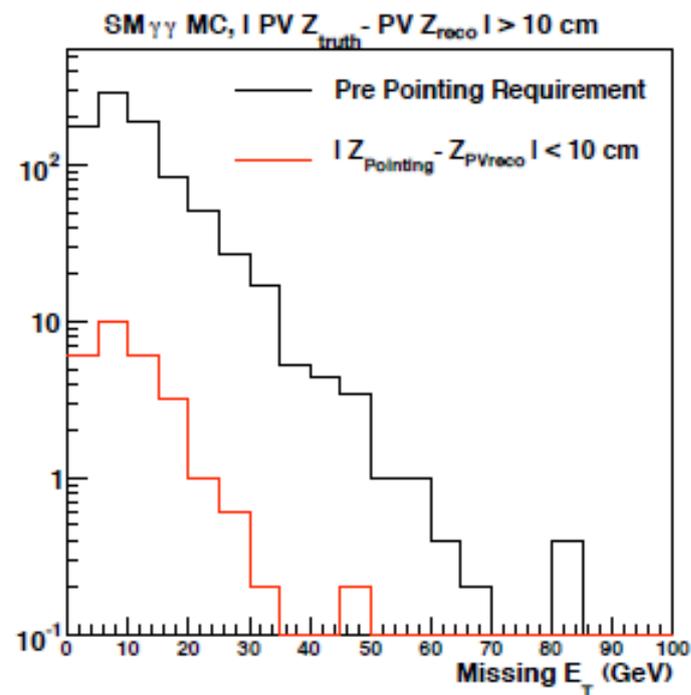
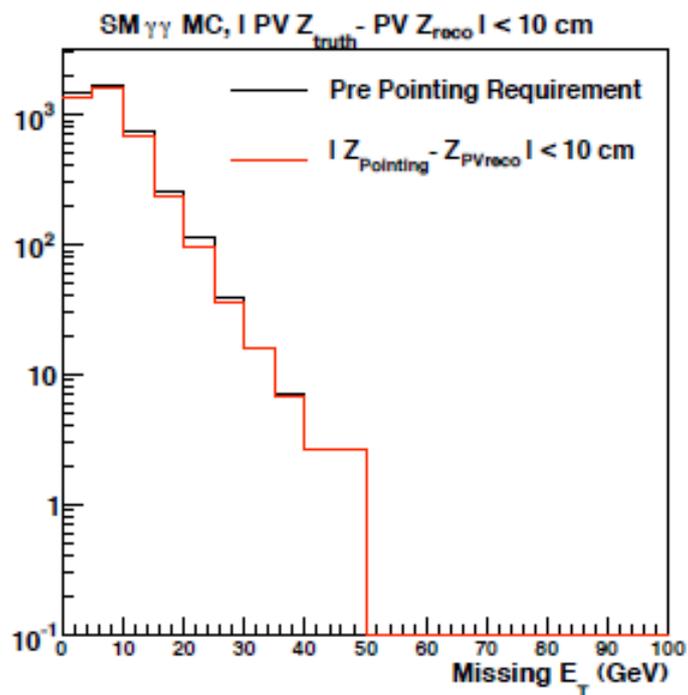
In events with jets, tendency for MET anti - alignment with leading jet. Signal MET relatively flat.





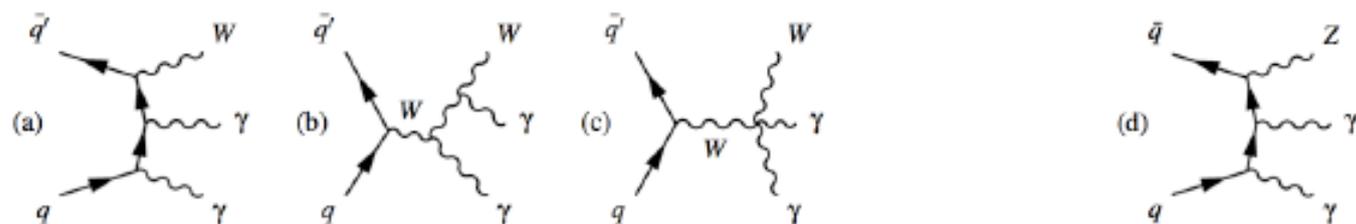
Primary Vertex Confirmation

- Primary vertex (PV) correctly identified with high efficiency (98%) in signal events.
- Less efficiently identified for SM backgrounds (e.g. SM $\gamma\gamma$) – potential for induced MET from PV misID.
- EM-CPS pointing used to confirm selected PV (MC demonstration below). Performance measured using $Z(\rightarrow ll)\gamma$ data sample (back-up). 6% less efficient in data than MC.



The W/Z+ $\gamma\gamma$ Processes and Prediction

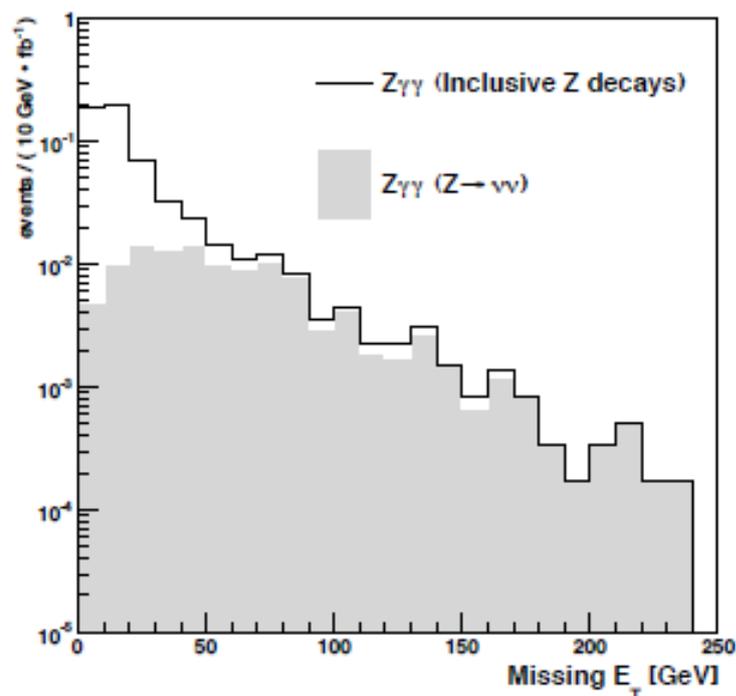
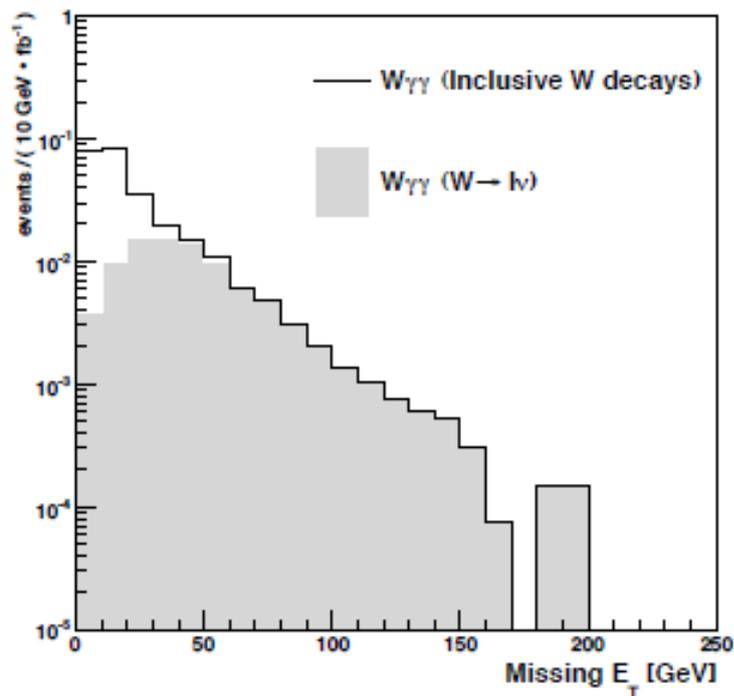
Rare SM $\gamma\gamma$ + MET processes estimated with fully simulated MC (MADGRAPH)



In 6.3 fb^{-1} , expect in $\gamma\gamma$ sample for inclusive decay modes and all MET values:

$1.64 \pm 0.13 \text{ } W\gamma\gamma \text{ events}$

$3.65 \pm 0.29 \text{ } Z\gamma\gamma \text{ events}$



Sample MC Signals

- Similar to previous Dark Photon analysis
- Use GMSB SPS8 point with chargino mass of 265 GeV and neutralino mass of 140 GeV and $\tan \beta = 15$
 - weak production: chargino pairs or chargino/second neutralino
 - use it mostly to create plausible kinematics: boosted dark photons plus MET, plus some jet activity from gaugino transitions
- Neutralino decays:
 - dark photon + darkino (50%)
 - dark higgs + darkino \rightarrow two collimated dark photons + darkino (50%)
- Radiation:
 - use no radiation, $\alpha_D = 0.1$ (some radiation), and $\alpha_D = 0.3$ (high radiation)
 - radiation is fairly soft, so impact on track efficiency seem to be low (in MC, at least)

$m(\gamma_D)$	0.15	0.3	0.5	0.7	0.9	1.3	1.7	2.0
$m(H_D)$	1.2	1.2	1.2	1.6	2.0	3.0	4.0	4.5

L-jet Isolation

Need isolation to separate from multi-jet background

But keep isolation loose enough to not kill possible signals!

- May have many more tracks, be wider from radiation, etc...

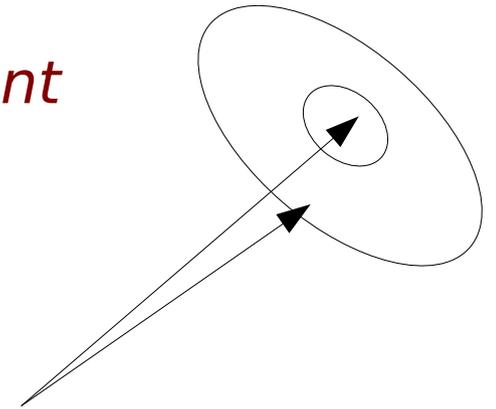
Track isolation: $p_T < 2 \text{ GeV}$ other than companion, in $0.2 < dR < 0.4$

Calorimeter isolation:

functions of l-jet p_T - don't bias MET measurement

Muon isolation in calorimeter $< .066 * p_T + 2.35 \text{ GeV}$
 $dR < 0.4$ and $dR > 0.1$ of either muon or companion track

Electron isolation in calorimeter $< .085 * p_T - .53$
 $0.2 < dR < 0.4$ in EM layers and $dR < 0.4$ in hadronic layers
(corrected for underlying event and pileup at high luminosity)





Event Selection

- Triggers

- MJ_MHT_HT, JT1_ACO_MHT_HT,
JT1_MHTACO, MJ_ACO_MHT_HT,
MJ_ACO_MHT_LM0, MJ_MET

- Jet

- $p_T^{\text{lead}} > 75 \text{ GeV}$, $|\eta| < 1.6$, JES
- $p_T^{\text{next}} < 25 \text{ GeV}$

- MET

- $\text{MET} > 50 \text{ GeV}$, JES-corrected, muons are not included,

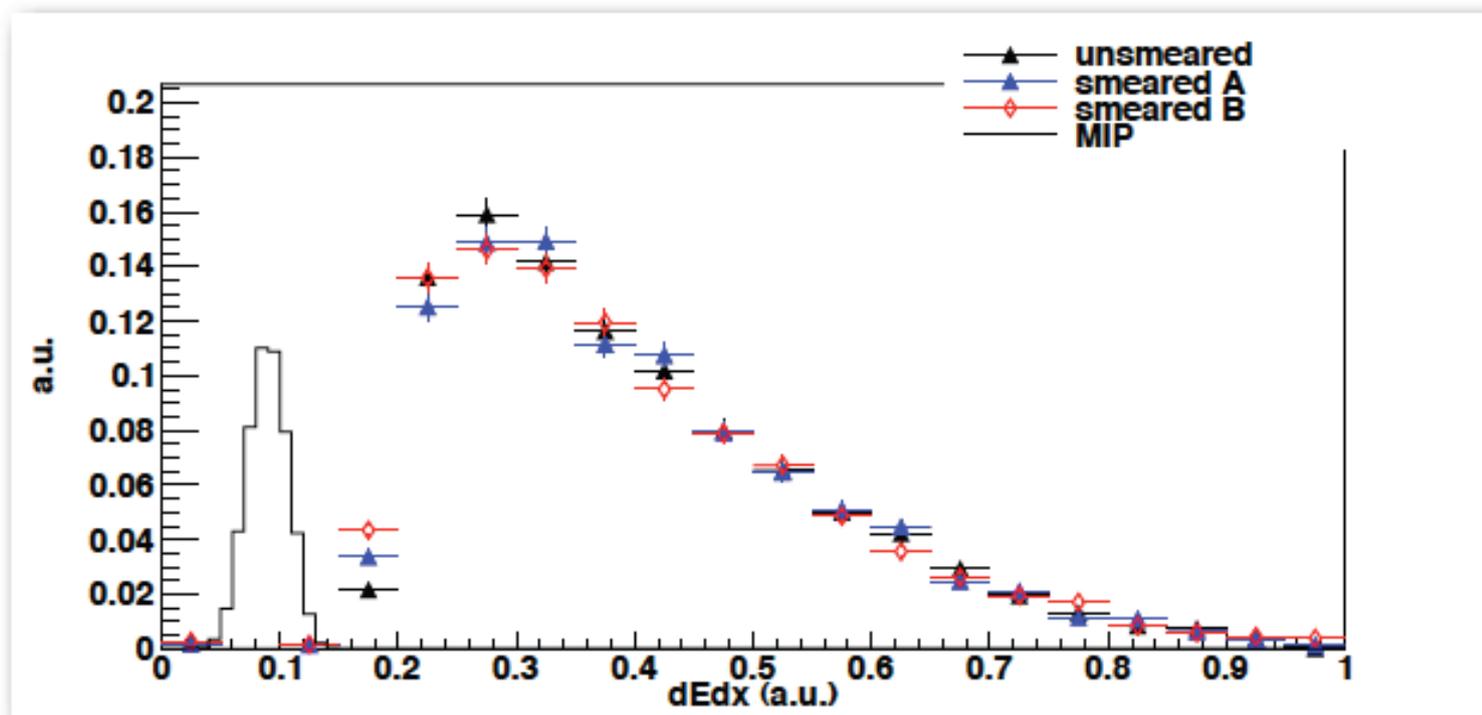
- Track

- $p_T > 40 \text{ GeV}$,
- $|\eta(\text{smt})| < 1.6$,
- $n\text{SMT} \geq 4$, $n\text{CFT} \geq 12$,
- $\text{trackiso} < 5 \text{ GeV}$ ($dR < 0.5$)



Smearing of dE/dx

- Theoretical distribution needs to be smeared
- We do so using width of MIP in data under two extreme assumptions:
 - the width of dE/dx distribution is mainly due to variation of energy deposition;
 - the width of dE/dx is dominated by the detector resolution.



- There is **no** sizable effect on efficiency of dE/dx cut